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FIRST RESULTS OF BUTTON BPMS AT FRIB*

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Abstract

Commissioning and tuning the linac driver for the Facility for Rare Isotope Beams (FRIB) requires a large network of warm and cryogenic beam position monitors (BPMs), with apertures of 40 - 150 mm, sensitivity to beam currents of 100 nA to 1 mA, and accurate for beams with velocities as low as 0.03c. We present initial results of the BPM system, analog and digital signal processing, and energy measurements for low energy beams.

COMMISSIONING AND TUNING

The Facility for Rare Isotope Beams (FRIB) is a new scientific user facility for low energy nuclear science. Under construction on campus and operated by Michigan State University, FRIB will provide the highest intensity beams of rare isotopes available anywhere [1].

The accelerator is being commissioned and tuned in sections. The Front End, RFQ, and first three superconducting RF cavities have been commissioned with beam [2]. BPMs are the primary tool used to determine beam position and beam energy. Beam of $^{40}Ar^{9+}$ was accelerated up to 2.3 MeV/u and BPM position and phase proved accurate down to currents as low as 100 nA. Figure 1 shows a portion of the linac and placement of 15 BPMs.

BPM Characterization and Correction

At FRIB, we primarily utilize two types of 4-button BPMs, with aperture diameters of 41.3 and 47.6 mm. Buttons are circular with 20 mm diameter. With a 4-button BPM, the simple formula (1) for position utilizes the ratio of difference over sum for two of the buttons signals (R, L or T, B) along with a scale factor incorporating the BPM aperture (D)

$$\mathrm{H} = \frac{\mathrm{D}}{\pi}\left(\frac{R-L}{R+L}\right), \quad \mathrm{V} = \frac{\mathrm{D}}{\pi}\left(\frac{T-B}{T+B}\right) \tag{1}$$

Formula (1) approximates beam position well, but distortion increases further away from center. A polynomial correction (2) was determined for each BPM type to correct for non-linear distortions. Each BPM was characterized using a translation stage to raster scan wire positions within the BPM aperture. Fiducials on the BPM housing, shown in Fig. 2, allow accurate position survey and correlation with pre-installation wire measurements to within 100 µm. Consistent BPM manufacturing allows the use of the same correction for all BPM assemblies of the same type.

$$\begin{aligned}\mathrm{H}_{\mathrm{new}} = p_{00} + p_{10}H + p_{30}H^3 + p_{50}H^5 \\ + p_{12}HV^2 + p_{14}HV^4 + p_{32}H^3V^2\end{aligned} \tag{2}$$

There is an additional position distortion present with very low-beta (v/c<<1) beams, resulting from the non-relativistic electric fields and asymmetrical pickup of the higher order beam harmonics when the beam is off-center [3]. = This effect is most significant when beta < 0.10, and can be ignored when beta > 0.15. Formula (3) corrects for low-beta distortion, where *a* and *b* are factors dependent on beta, frequency, and geometry [3].

$$\mathrm{H}_{\mathrm{new}} = a\mathrm{H} + b\mathrm{H}^5 \quad \mathrm{V}_{\mathrm{new}} = a\mathrm{V} + b\mathrm{V}^5 \tag{3}$$

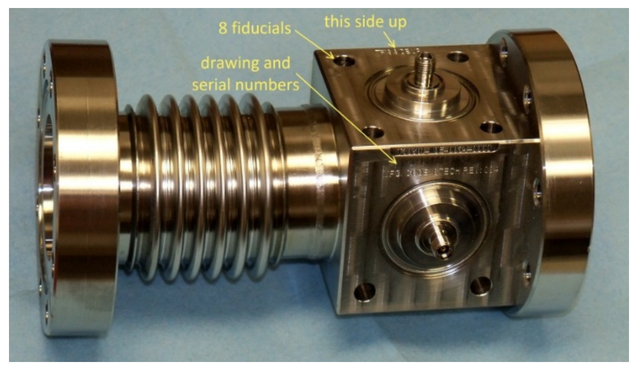

Figure 2: FRIB BPM assembly.

DAQ ELECTRONICS AND SIGNAL PROCESSING

The BPM data acquisition electronics were designed to be MicroTCA [4] based, where up to 10 BPM electronics boards communicate (using PCIe) to a single CPU which serves data to the control system network. The electronics consist of a rear-transition module (RTM) which includes +35 dB amplification, analog filter (either lowpass or bandpass), and ADC digitization. This RTM digitizes two 4-button BPMs plus a reference (REF) clock. An FPGA digital processing board performs digital down-conversion

Figure 1: A portion of the FRIB linac, including medium energy beam transport (MEBT), first 3x cryo-modules with 12x accelerating SRF cavities, and diagnostics station as temporary beam stop. 15 BPMs locations were studied, 6 of which were “cold” BPMs inside cryo-modules.

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and digital signal processing of the 2nd harmonic of the 80.5 MHz bunch rate (161 MHz). These boards are pictured in Fig. 3 and a MicroTCA chassis installation in Fig. 4. Polynomial distortion correction and low-beta corrections are applied in software by the CPU. The thermal noise floor was noticed to be equivalent to ~ 30 nA beam current in the Front End.

Figure 3: RTM digitizer board and FRIB FPGA board.

Figure 4: MicroTCA chassis with 8x BPM electronic boards, digitizing up to 16 BPMs.

Analog Front-End Electronics

BPM electronics boards are built with two variations; low-pass and band-pass. The 161 MHz signal is used for all position and phase reporting, so a band-pass filter between amplification stages will result in lower noise, due to fewer noise bands aliased to the frequency of interest after digitization. However, the low-pass filter allows additional beam harmonics to be digitized, making possible some interesting future signal processing and data reporting, not discussed here. The +35 dB amplification was implemented as shown in Fig. 5, such that the noise floor was dominated by thermal noise in the first amplification stage, but with ADC noise floor only 6 dB lower, which best utilizes the ADC dynamic range.

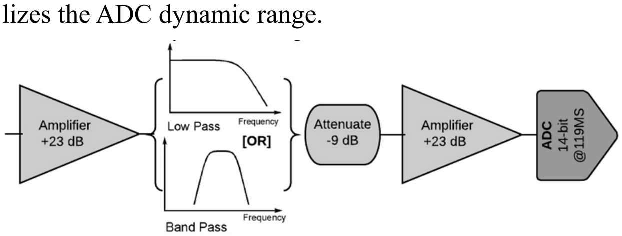

Figure 5: RTM analog front end block diagram.

Digital Signal Processing

The 161 MHz signal is digital down-converted to baseband IQ, integrated over various time intervals, and reported. The FPGA gateware calculates BPM position, magnitude (intensity) and phase every 100 Hz, integrating over 10 msec. This 100 Hz data is sent to the CPU which performs further processing, including the 1-sec time average for position, intensity and phase. The CPU also applies polynomial and low-beta position corrections and other position / phase offsets from survey and electronic calibration measurements.

BEAM MEASUREMENT RESULTS

Figure 6 below shows a snapshot of the BPM intensity and position measurements during recent linac commissioning activities. The BPM intensity is the magnitude of the 2nd harmonic of the beam bunch rate. As the beam is accelerated within a stable RF bucket, the 2nd harmonic intensity is observed to increase and then oscillate. BPM #1-4 only see acceleration from the RFQ and BPM #5 is the first to see SRF acceleration. BPMs #13-15 reside in a final diagnostic drift section.

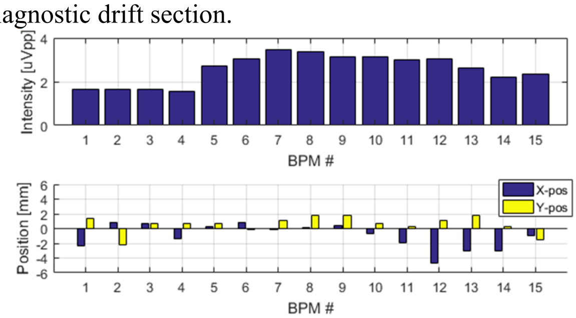

Figure 6: BPM intensity and position during linac tuning.

BEAM ENERGY MEASUREMENT

The primary responsibility of the BPMs is to track beam position, but BPMs also support important beam energy measurements. Beam energy can be determined using time-of-flight (TOF) measurements between BPMs. Estimating TOF using BPM phase results in some ambiguity, if multiple phase periods occur between pickups. This ambiguity can be resolved by using three BPMs which have different distances between them in a region where beam energy is known to be constant. See [5] for a description of this approach.

$$\text{Energy [MeV/u]} = m_0 c^2 \left(1/\sqrt{1-\beta^2} - 1\right) \quad (4)$$

$$\beta = v/c = L/tc \quad (5)$$

Relativistic beam energy can be calculated knowing the mass m_0 and velocity. Velocity is determined by physical length between BPMs, *L*, and beam transit time *t* between BPMs. This can be determined from the signal phase difference between BPMs, but consider two practical problems. Phase difference yields time difference, but with unknown number of full periods. Distance between BPMs is often long enough that multiple bunches fit in the space. Also, signal transmission times often differ between BPMs, including electronics and long run cabling differences, which must be accounted for.

BPM System Calibration

In addition to physical survey of BPMs locations, we characterize the signal delay differences introduced by long run BPM cables and small electronics variations. Each

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group of 4 long run cables for a BPM have been phase-matched and trimmed to within 1° phase at 80.5 MHz, but it was not practical to trim all BPM cables to the same length throughout the machine. Our BPMs report signal phase relative to an 80.5 MHz reference (REF) clock distributed throughout the machine and to each BPM DAQ board. This same REF clock system is used by the RF accelerators and bunchers. To measure the signal delay contribution from long run cables and DAQ electronics, a signal is generated near the BPM device which is phase-locked to the REF clock. This signal is split 1:4 and connected to the long run cables for a single BPM, and the phase is recorded. The same REF clock signal cable is used to measure all BPMs, one at a time. These BPM phases represent the offset due to cabling and electronics, and must be subtracted prior to beam energy estimation. Figure 7 shows an example where BPM #6 cables and electronics are being measured for calibration using REF clock.

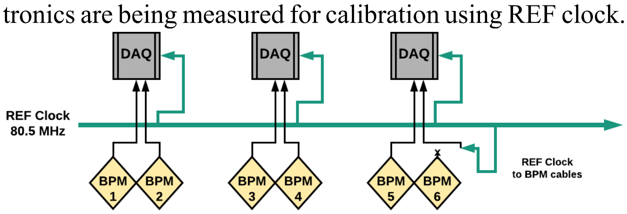

Figure 7: BPM system calibration diagram.

Short 1 meter patch cables exist on both ends of the long cables. The device side patch cables were not measured during the calibration procedure. If all patch cables were the same length, this would not be relevant, but in our case, two types of patch cables were used for warm and cold BPMs. The cold BPM patch cables add an additional 36.5° phase, which was also subtracted for cold BPMs only.

Energy Calculation and Uncertainty

The approach described in [5] involves using 3 BPM pickups; one pair closely spaced, for coarse velocity estimation, and one pair spaced far apart, for better velocity accuracy. Our BPM installation does not allow for BPMs placed close together, so we need a more general approach. We use 3 BPMs to generate 3 pairs, each with different spacing. Each of these pairs has some energy uncertainty, due to unknown number of full periods, but we can determine the real energy by noticing where these possible energies overlap, giving the same answer in all three cases.

In any real system, there are error sources which prevent the energy estimates from giving an exact match. Sources of additional variance and uncertainty includeposition survey accuracy, accuracy of cable calibration, and signal phase noise. The last is largely a function of beam intensity and the signal/noise performance of the front-end electronics. Adding the variances from these sources is fairly straightforward, assuming they are uncorrelated and represented by normal distributions. In our case, typical stack-up of uncertainties resulted in an RMS phase uncertainty of about 0.5°.

We incorporate these uncertainties by modelling a normal distribution centered at each possible energy estimate, which generates a pseudo-probability distribution for each BPM pair. The joint energy probability distribution is estimated by a point-by-point multiplication of the three individual distributions. We report the peak value of this combined probability distribution, which is itself properly weighted; BPM pairs with less uncertainty have more impact on the final answer. Figure 8 illustrates this approach using real data from 3 BPMs, showing beam energy of 2.011 MeV/u. For improved visibility of normal distributions, variances for the normal distributions in this figure were exaggerated to 10° (instead of the actual 0.5°).

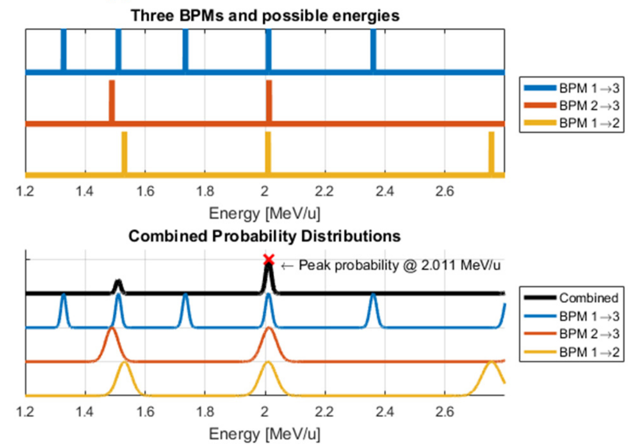

Figure 8: Beam energy calculation using 3 BPMs.

CONCLUSION

The BPM system is supporting linac commissioning, with beam currents as low as 100 nA. Beam of $^{40}Ar^{9+}$ was accelerated from 0.5 MeV/u at the exit of the RFQ to 2.3 MeV/u after 12 SRF accelerating cavities in 3 cryomodules.

Polynomial corrections and low-beta corrections performed as expected to improve BPM accuracy when beam is not centered. Using calibrated BPM phase results, we calculated beam energy to 1% accuracy. Our BPM energy calculation algorithm is flexible enough to use any three BPMs in a combined manner for very high accuracy. The full linac, when complete, will have 150 BPMs distributed throughout the machine. Our approach will allow real-time, non-intercepting beam energy reporting at any point in the linac.

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