BEAM POSITION MONITORS FOR LEReC*

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Abstract

The operating parameters for Brookhaven National Laboratory's Low Energy RHIC Electron Cooling (LEReC) project create a unique challenge. To ensure proper beam trajectories for cooling, the relative position between the electron and the ion beams needs to be known to within 50µm. In addition, time of flight needs to be provided for electron beam energy measurement. Various issues have become apparent as testing has progressed, such as mismatches in cable impedance and drifts due to temperature sensitivity. This paper will explore the difficulties related to achieving the level of accuracy required for this system, as well as the potential solutions for these problems.

INTRODUCTION

The LEReC project has strict requirements for position and phase measurements. The ion beam has a repetition rate of 9 MHz and the electron beam has a repetition rate of 704 MHz. Two sets of electronics are planned for handling the low frequency and high frequency signals. The typically operation will have 704 MHz bunch trains to overlap the ion beam (Fig. 1). For the electrons to properly cool the ion beam they must be travelling at the same speed with an angle of less than 100 µrad between the beams [1]. To ensure sufficient cooling, the difference between the electron beam and the ion beam must be measured with 50 um accuracy. The challenge with this level of accuracy is the difference between the frequencies of the two beams which creates disparate responses in signal processing. Due to difficulties associated with absolute calibration of BPM electronics, a relative measurement between the two beams is planned.

. During the initial testing, the BPM system will also be responsible for making phase measurements that can be used to calculate the energy of the electron beam. These phase measurements must have a resolution of 0.25 degrees at 704 MHz to give the necessary 1ps resolution for time of flight between BPMs placed several meters apart, in order to provide the required energy resolution of roughly 2E-4 at 400KeV [1].

Several design challenges exist including, synchronous phase measurements across all BPMs, unacceptable errors due to temperature sensitivity of the cables which affect attenuation and cable delays, and matching the high and low frequency signal responses for relative position measurements.

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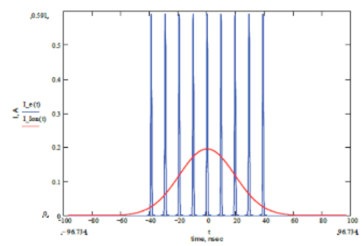

Figure 1: Electron bunches (blue) overlapping with ion bunches (red). [2]

HARDWARE ARCHITECTURE

The LEReC BPM pickups use 9mm, 15 mm and 28mm buttons oriented along the x and y planes of the machine [2]. The electronics for processing the data from the buttons will be located in a nearby equipment building and will require cable lengths greater than 200 feet, partially routed outdoors. The long cable lengths introduce severe attenuation of the higher frequency 704 MHz electron signal.

Due to the difficulties associated with accurately measuring electron and ion beam signals with different base frequencies, two different analog front ends planned to be used to pre-process the signals. The most significant difference between the two sets of analog front ends is the filters. For low frequency ion and electron measurements a 39 MHz low pass filter will be used and for electrons a 707 MHz band pass filter will be used (Fig. 2). The 9 MHz macrobunch structure of the electron beam signal creates a strong response when the signal is processed at 9 MHz, allowing the electron and ion beam signals to be processed with the same electronics. Diplexers will be mounted in the racks to separate the low and high frequency signals. There will be an RF switch module mounted in the tunnel, the purpose of this module will be explained later in the paper.

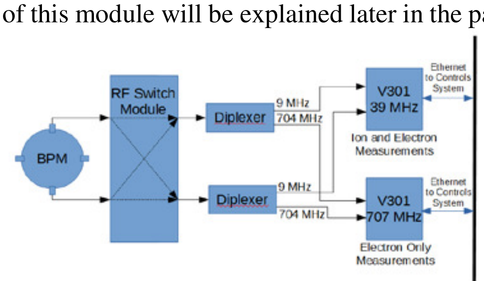

Figure 2: The basic configuration showing how BPM signals are connected to the processing electronics. The 39 MHz electronics measures both electrons and ions.

Libera BPM electronics from a previous project will process the signals in the transport section of the electron beam line. The remaining BPM signals will be processed using in-house designed V301 modules, which are based

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on a ZYNQ SoC containing an FPGA and a microprocessor on the same die. This architecture provides an incredible amount of flexibility for processing data [3].

PHASE MEASUREMENT TECHNIQUE

Achieving the desired one picosecond resolution for time of flight requires a phase measurement with a resolution of approximately 0.25 degrees. Phase measurements with this resolution must be made at multiple BPMs with a common reference in order to be useful.

One common method for measuring phase is to down convert relative to a distributed reference signal. The BPM electronics that are being used for LEReC were not initially designed with phase measurements in mind. However, a solution has been found. A digital recreation of the 704 MHz RF clock will be produced in each V301 module to provide a common reference for phase. The RF clock for LEReC is generated using a 100 MHz master clock and a direct digital synthesizer driving a 400 MHz digital to analog converter. By converting the 100 MHz reference clock to 400 MHz to drive both the analog to digital converters and the direct digital synthesizer, the RF clock can be accurately reproduced. The phase of the electron beam at a BPM relative to this RF clock can then be calculated using IQ demodulation (Fig. 3). The phase is then the inverse tangent of the in-phase and quadrature components of the output of the demodulator.

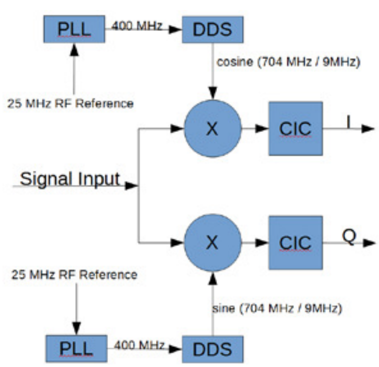

Figure 3: Block diagram of the digital IQ demodulator. Both direct digital synthesizers (DDS) blocks refer to the same synthesizer with sine and cosine outputs. The cascaded integrator comb filters (CIC) decimate the signal by a factor of 512.

Demodulation using a common clock does not provide a sufficient measurement by itself. The BPMs have different cable lengths between the pickups and the electronics. Although the length of each cable can be measured, the overall time of flight on the cable is not actually required. Instead, a function generator can be placed at the far end of the cables sending the same signal to multiple channels. A phase offset can then be introduced in the BPM electronics to zero the phase relative to the sine wave produced by the function generator. Zeroing all electronics against the same function generator using the same master clock while including the different cable delays ensures that the observed phase difference between the BPMs is the actual change in phase of the electron beam relative to the RF clock.

PHASE MEASUREMENT TEST

To test the quality of the phase measurements that can be achieved using the above described technique a test signal needed to be created that would be respectably similar in nature to the expected electron signal. To generate this signal, two function generators, an Agilent 8448C and a Tektronix AFG3202, were use alongside a Model 3600 impulse generator from Picosecond Pulse Labs (Fig. 4). The Agilent function generator was used to generate a 700 MHz sinusoidal signal to clock the impulse generator, while other Tektronix function generator was used to “gate” the impulse generator to simulate the 9MHz macrobunch structure. The impulse generator output from this setup was a 700 MHz train of 70ps bunches with a 9MHz structure (Fig. 4).

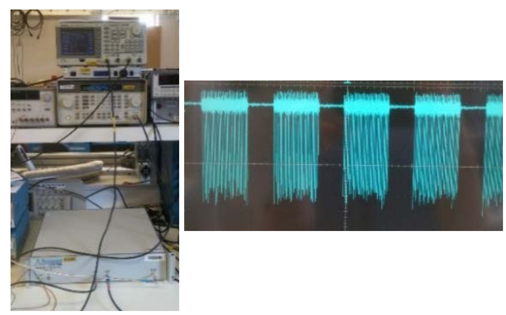

Figure 4: The picture on the left shows the test setup used to generate the 704 MHz pulse train test signal with 9MHz macrobunch structure. The picture on the right shows the resulting test signal.

The simulated signal was split, with one output of the splitter connected directly to the input of the V301. The other splitter output was passed through a coaxial phase shifter. The phase shifter was used to delay one input of the V301 so that the phase difference between the two channels would be tuneable. The delay at the output of the phase shifter changes by 2.45 degrees per turn, with a precision of 0.35 degrees. The output of this variable delay line was then inserted into another channel of the V301.

The goal was to measure the change in relative phase between the two channels.

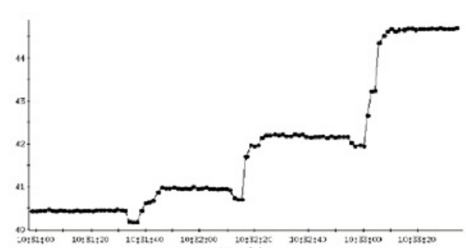

Figure 5: Phase difference in degrees between two channels of the electronics as the delay on one channel was increased.

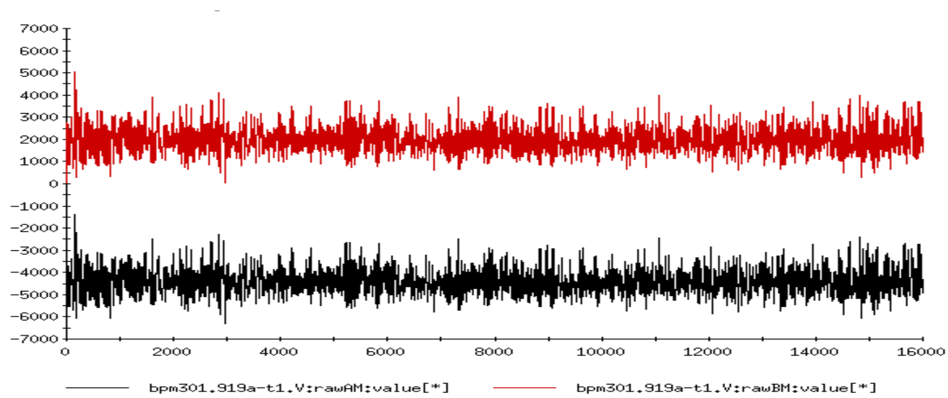

Figure 6: Raw phase measurements from two channels of the V301. The peak to peak is approximately 4000 counts, which equates to 110 degrees.

The results of this test showed that the phase could be measured to within 0.1 degrees when using multiple channels on the same module (Fig. 5). However, phase measurements of a single channel are quite noisy. The noise in the phase measurement is common to both channels, so the noise is completely eliminated when one channel is subtracted from the other (Fig. 6).

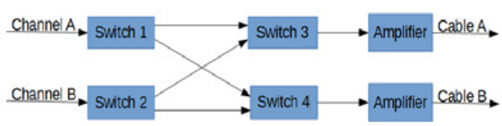

Figure 7: A block diagram of the switch configuration. In the default switch position, switch 1 is connected to switch 3 and switch 2 is connected to switch 4. A logic high connects switch 1 to switch 4 and switch 2 to switch 3.

The ultimate goal for phase measurements is to observe the relative phase measured by two different sets of electronics. This will require a single phase measurement with low noise that can then be compared with a phase measurement from another set of electronics. The phase measurements of different channels from the same BPM can be averaged together over a sufficiently long period of time to improve the quality of the phase measurements before delivering the data.

DRIFT CORRECTION

One of the challenges regarding position measurements for LEReC are the changes in the cable losses as temperature changes for a 704 MHz signal. Due to their length, the cables connecting the BPM buttons to the electronics introduce significant attenuation for the high frequency electron signal of approximately 20 decibels. By itself, this problem can be solved by using amplifiers, but changes in temperature throughout the day slightly change the losses in the cables. The change of attenuation in a cable is typically not the same as the change of attenuation of any other cable. This asymmetrical change in cable losses creates an offset in position that can change throughout the day. An amplitude imbalance of +/- 0.05 dB equates to a position shift of 50 microns. The small changes in the cable losses are enough to create errors greater than 50 microns.

To counteract this effect, switches will be placed in the tunnel near the pickups (Fig. 7). These switches will swap signal pairs from a single plane. If no offsets exist downstream of the switch, then the position in that plane should be equal and opposite. When an amplitude imbalance exists downstream of the switch, the position will instead reflect around a nonzero point that can be found by averaging the position before switching with the position after switching. The value of this average is the position offset created by the amplitude imbalance. This offset can then be eliminated by either scaling one or both of the channels, or by subtracting the offset value from the final position measurement.

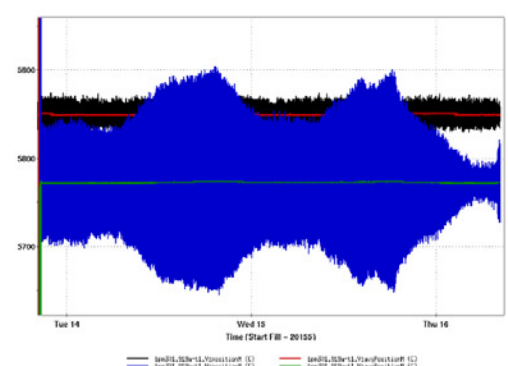

Figure 8: The blue and black show positions calculated from a pair of cables that were actively being switched. The envelope of the blue represents the changes due to temperature. The green and red are the average positions.

By automating the control of these switches using the V301 electronics, the switching can be performed at regular intervals with the cable offsets removed seamlessly (Fig. 8).

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MATCHING LOW AND HIGH FREQUENCY RESPONSES

To measure both the ion and electron signals from the same BPM pickups, the signal will be diplexed and sampled with V301 modules with different RF front ends. The lower frequency 9 MHz ion and electron train signals can be oversampled with a 400 MS/s sampling rate with all additional processing taking place digitally. The 704 MHz electron signal is bandpass filtered with a 707 MHz saw filter before being sampled at the same 400 MS/s rate. The position of the 704 MHz electron can be calculated using the same IQ demodulation process required by the phase measurement. The magnitude of each channel is the square root of the sum of the squares of the in-phase and quadrature signals. From the magnitude, the position is simply the difference divided by the sum.

The ion signal will be processed using a similar method. However, the electron beam has a 9MHz macrobunch structure which will affect the amplitude measurement of the ion beam. This macrobunch structure can interfere with the ion measurements, but it can also be used to cross-calibrate the high and low frequency electronics. The response of the low frequency electronics after filtering with a narrow band digital filter will be similar between the ion and electron signals owing to the 9 MHz component of the electron signal. In the absence of an ion signal, the electrons can be measured with both sets of electronics to determine the calibration coefficients required to match their responses. The 9 MHz component of the electron beam will also prevent accurate ion measurements, so the electron beam will need to be shut off periodically to allow the ion signals to be measured without interference.

CONCLUSION

Various methods have been outlined that will enable the BPM system to meet the requirements for LEReC. IQ demodulation with a synchronous reference will be used for phase measurements. Switching modules will be installed in the tunnel to remove errors introduced by temperature variations. The 9 MHz and 704 MHz responses of the electron beam signal will be used to cross-calibrate the electronics.

The solutions discussed for correcting drift and measuring phase have limitations, and further development is necessary. There is a significant amount of jitter associated with the phase measurements using IQ demodulation. To compare the phase measurements made by two different sets of electronics will require longer averaging to eliminate jitter before the data can be delivered.

The proposed method for eliminating observed position drifts also has limitations. The switches have transients with durations greater than 50 ns. Although short, the position measurements are affected for 5 µs. This is an undesirable effect of the switches as it does not allow us to meet the requirements for the MPS system. Several additional solutions need to be explored, including reducing the switching transients by subtracting the transients from two switches as was done at SuperKEKB [4].

With some additional development, the beam position monitoring system is expected to be on track to satisfy the requirements for LEReC.

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REFERENCES

[1] T. Miller et al. “LEReC Instrumentation Design and Construction,” *IBIC 2016*, Barcelona, Spain (2016), paper TUPG35.
[2] A.V. Fedotov et al. “Bunched Beam Electron Cooler for Low-energy RHIC Operation,” *NA-PAC 2013*, Pasadena, USA (2013), paper TUOAA1.
[3] R. Hulsart, et al., “A Versatile BPM Signal Processing System Based on the Xilinx Zynq SoC,” *IBIC 2016*, Barcelona, Spain (2016), paper WEPG12.
[4] H. Fukuma et al. “Beam Instrumentation for the SuperKEKB Rings,” *IBIC 2012*, Tsukuba, Japan (2012), paper MOCB01.