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BEAM POSITION MONITOR CALIBRATION BY RAPID CHANNEL SWITCHING*

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Abstract

One of the requirements for low-energy RHIC electron cooling (LEReC) is a small relative angle between the ion and electron beams as they co-propagate. In order to minimize relative electron-ion trajectories angle, BPM measurements of both beams must be very accurate. Achieving this requires good electronic calibration of the associated cables and RF components, due to their inherent imperfections. Unfortunately, these are typically frequency dependent, especially in the RF filter and amplifier stages. The spectral content of the ion vs. electron bunch signals varies significantly, presenting a calibration challenge, even when using the same sampling channels and electronics to measure both beams.

A scheme of rapidly swapping the BPM signals from the pickup electrodes between the two signal cables (and sampling channels), using switches installed near the BPM was implemented to combat these calibration issues. Bias in each signal path appears as an offset which has an equal and opposite component when the cables are reversed. Taking the average of the two measurements with the channels in normal and reverse positions reduces this offset error. Successful transverse cooling of the RHIC ion beam has been verified after using this switching technique to provide continuous calibration of the BPM electronics [1]. Details of the processing hardware and switch control methodology to achieve this result will be discussed.

INTRODUCTION

Beam position measurements in accelerators are commonly performed by sampling the induced signals on a pair of pickup electrodes mounted in the vacuum chamber. In order for them to be precise and accurate, small differences in signal amplitude need to be measured between these two sampling channels. In most BPM systems, separate analog signal paths consisting of cables, amplifiers, attenuators, and filters are used to process each signal before being sampled by an analog to digital convertor (ADC). Each of these circuit elements has inherent properties that can attenuate or reflect signals with a dependence on frequency.

Typically, a calibration procedure is followed by using a known test signal to match the gain and offset of each of these channels, in order to balance their response. In theory once these channels are matched the true position of the beam will be the only contributor to any difference. In reality, the circuit response due to the test signal can differ significantly from that produced by a real beam. There are also accelerators where the spectral content of the beam signal can change during operation due to variations in RF frequencies such as with rebucketing. The presence of two beams of different bunch length and/or structure also has the same effect of changing the response of the individual circuit elements of each sampling channel. This leads to a situation where a static calibration using a test signal is inadequate to remove the electronic offsets for all beam conditions. Another source of offsets that can't be removed with static calibrations is the presence of radiofrequency interference (RFI) at the bunch frequency or its harmonics picked up by the long cables and enhanced by ground-loops. Such RFI can vary with time and can produce offsets that are bunch-intensity dependent.

One method of removing these offsets is to periodically swap the channels that each of the pickup electrodes (PUE) is connected to. By placing a set of switches close the BPM, each PUE can be connected to either of the sampling channels, including cables, analog processing electronics, and ADC. When using a BPM with two PUE's, this will produce two separate position measurements, where the differences due to the sampling channels are equal and opposite in sign. By rapidly switching and averaging these two together, a true measurement is obtained that is free from the offsets produced by elements downstream of the point of switching.

SWITCHING TECHNIQUE

Theory of Operation

To simplify this description, we will consider a single plane BPM measurement derived from two PUE's. An enclosure containing an arrangement of solid-state transistor switches is placed close to the BPM and connected via short cables. We will call these PUE signals A and B and these are the inputs to the switch. The outputs will be labelled 1 and 2 and are connected via longer cables to the BPM processing electronics.

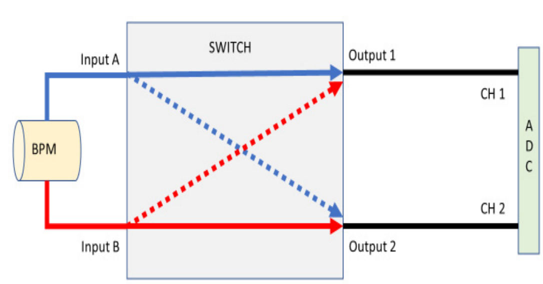

Figure 1: Switching Block Diagram.

The switch circuit is designed such that in the 'Normal' position, input A is connected to output 1 and B is connected to 2. When a control signal is applied to the switch,

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it changes to the ‘Reverse’ condition, where input A goes to output 2, and B to 1. The resulting situation is that any difference between A and B gets inverted when the switch position is changed, however, any difference that appears after the switch between 1 and 2 will remain unaffected. Figure 1 illustrates this in block form.

Since the arrangement of PUE’s A and B are related to the sign convention of the accelerator, the calculated position needs to be inverted in sign when the switch is in the reverse position, because the PUEs are now reversed with respect to the beam direction through the BPM. By inverting the calculation when the switch is in the ‘Reverse’ position, the true position produced by the beam will remain correct in sign. The offset that exists due to differences between paths 1 and 2 will also change sign, and so appear as an equal but inverted offset when combined with the true position from the BPM. This has the effect of producing two positions, one equal to ‘true position + electronic offset’ and the other ‘true position – electronic offset’. By observing this envelope one can separate the beam position from the electronic offset. In addition, by rapidly switching back and forth, the mean of these two measurements will remove the offset, and only include the true position. A more complete derivation of this process is explored in a technical brief [2].

Switch Control Methods

A few considerations need to be accounted for in order to realize such a switching system. It is possible to separately control the switch position where the BPM electronics is not aware of the reversal. In this case the position data can be altered (inverted) manually or by separate software that is aware of the switch position. Such a system can still be useful for ‘slow’ calibrations that are periodically performed. In this case the calibration constants of the BPM channels would be adjusted such that there is no longer any difference between ‘Normal’ and ‘Reverse’. This type of application would have to be periodically checked to deal with dynamic beam spectral changes or changes due to thermal drifts over long time scales.

To provide continuous and automatic calibration, especially with high repetition rate beams, it is better to allow the BPM electronics itself to control the switching. In this case a control signal is provided as an output from the BPM processor, and the internal calculation will invert the measurement whenever the switch is in the ‘Reverse’ position. Such a system was realized for the LEReC project using the BNL designed V301 BPM processing electronics [3].

BPM SWITCHING FOR LEREC

The requirement to co-propagate ion and electron beams with minimal angle between electron and ion trajectories for the LEReC project was a driver for the realization of this type of BPM switching system. Even though the repetition rate of the ion and electron bunches were similar (9 MHz spacing), the spectral content of each were not, since the ion beam consisted of a train of single long bunches whereas the electron beam ‘macrobunch’ consisted of a series of 704 MHz spaced short bunches with an overall 9 MHz modulated structure. Due to these differences, the calibration coefficients needed to balance the offsets of the electronic channels are not the same for each case. In order to be able to use the same processor to measure both beams accurately, the switching system described herein was realized.

LEReC Switching Hardware

A custom hardware module was designed at BNL to perform the channel switching. A set of four GaAs FET RF switches (Analog Devices HMC349) are arranged in a manner which allows the input signals A and B to be swapped to either output, 1 or 2, simultaneously. Great care was taken in this PCB design to closely match each part of the circuit, for both IC placement and routing of the traces on the board. A single 5V control signal is common to all four switches, which causes them to change state in unison. Each of these switches has a small insertion loss which did not differ significantly from part to part. During testing of about 30 units, negligible offset contributions were measured from the switches themselves. See figure 2 for a circuit schematic. More details are also available in an earlier comprehensive LEReC BPM system description[4].

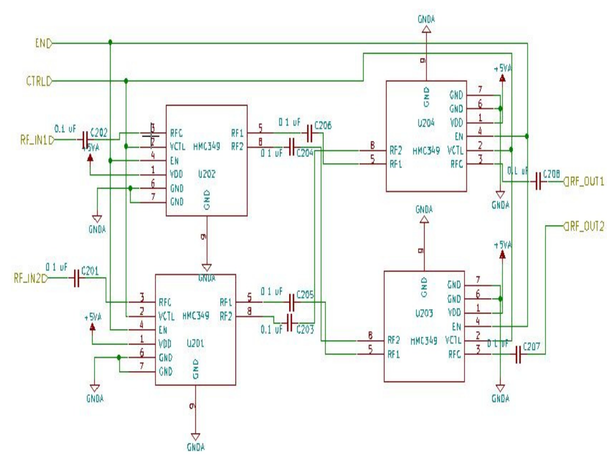

Figure 2: Switching Circuit Schematic.

LEReC Beam Measurements with Switching

During the commissioning of the LEReC the switching technique was carefully scrutinized. During assembly of the electron accelerator a test signal using a well-matched splitter was injected into each BPM signal path close to the BPM itself. The test signal used was a 704 MHz sine wave modulated at 9 MHz (similar to the electron beam macrobunch). Gain and offset coefficients were adjusted for each BPM to obtain a zero position reading.

Once electron beam was available in the ‘pulsed’ 1 Hz mode using only a few macrobunches, the switches were manually moved between the ‘Normal’ and ‘Reverse’ positions. As expected, many of the BPMs no longer appeared well calibrated (showing a change between the two switch positions), due to differences between the test signal and real beam signal. The calibration settings were then manually adjusted again to remove any differences. When ion beam was present in the same BPMs, the same proced-

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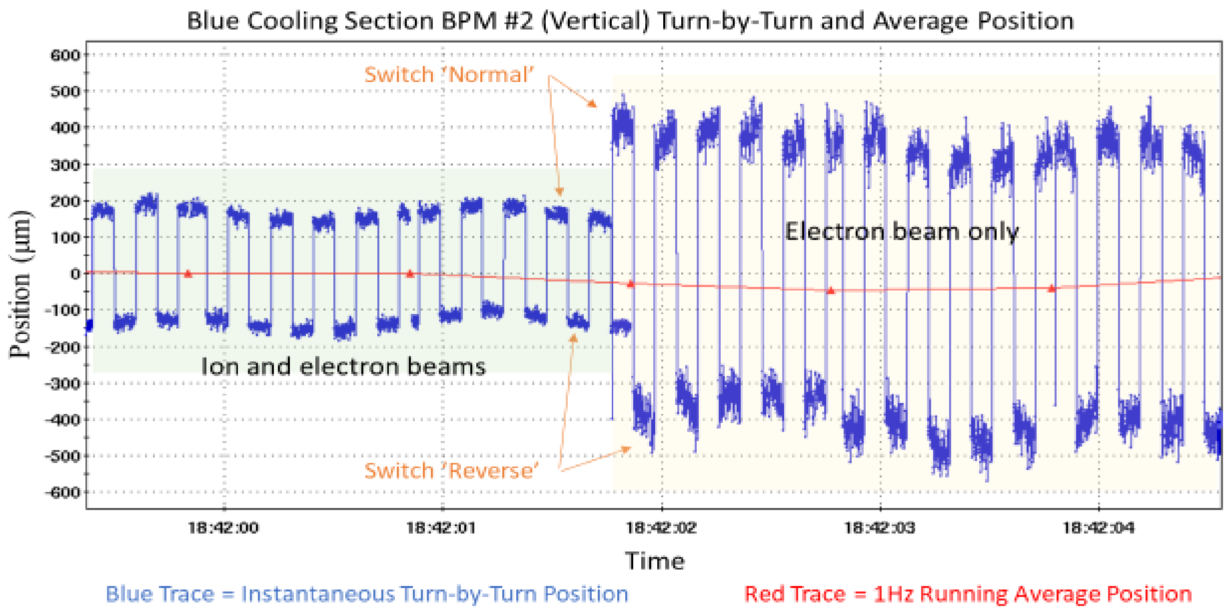

Figure 3: Calibration difference with ion and electron beam (left) vs. electron beam only (right).

ure was followed, and as expected, differences due to switch position were again present. The switches were then commanded to switch automatically every 100 RHIC turns (approximately a 760 Hz rate for a 76 kHz revolution frequency). A running average position was calculated by the BPM processor that had a cutoff frequency of a few Hz, thereby smoothing out the two positions derived from the switching. Regardless of the calibration values for each channel (to a reasonable magnitude) no artifact of the switching envelope remained, thereby providing a smooth and constantly calibrated position reading from the BPMs regardless if ions or electrons were being measured.

Figure 3 illustrates the differences in calibration very clearly during the moment that the ion beam in RHIC was removed. In this particular case the ion beam intensity was several times higher than the electron beam, so that it dominated the BPM response when both beams were present (therefore the response shown on the left is nearly identical with ion beam alone). When the ions were removed it is evident that the position appears to have shifted by ~200 µm when looking at the turn-by-turn data in either switch position. The average of these two positions remains the same however, which illustrates that this offset comes from a source downstream of the switches, and not the beams themselves. This was further verified by the fact that transverse cooling was evident (using other instrumentation) when the beams were aligned based on these BPM measurements. Note that the time axis in this figure is not continuous – only 1024 turns are reported each second, despite the revolution frequency of ~76 kHz. The jumps in the position correspond to changing the switches every 100 turns.

Drift Compensation

By running the switching in this continuous mode, long-term drifts due to thermal effects are also compensated for. Any changes in attenuation in the long cables running out of the tunnel due to temperature will be averaged out by this same method. In addition, thermal effects within the electronics, both in the filtering stages and amplifiers, also benefit from the same averaging. Figure 4 shows the result when a test signal was applied to a LEReC BPM where the envelope of the turn-by-turn data can be seen to change by ~40 µm as temperature is changing (top plot) by ~4°C due to air conditioner cycling in the equipment building. The average position (red trace) however remains almost unaffected.

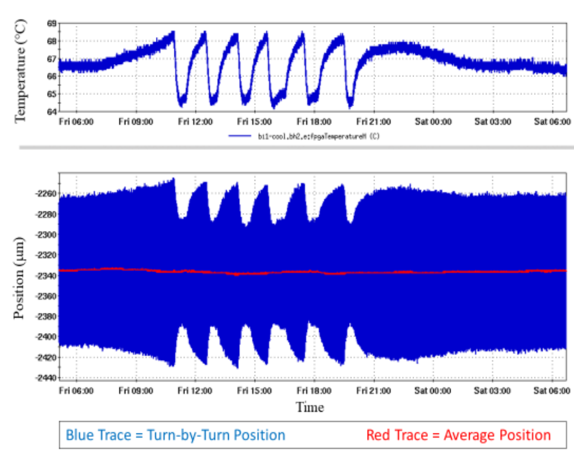

Figure 4: Drift over 24 hours due to temperature.

SWITCHING TRANSIENTS

One of the major issues presented by using FET solid-state switches to perform the channel switching is the presence of transients induced by the switches themselves each time they change state. This effect is also known as 'video feedthrough' and is an inherent effect of the FET device. There are other means of switching, such as using mechanical relays, that could be used as an alternative to solid-state

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devices, although there are other issues that these devices could present as well.

In this application, it was decided to deal with the transients produced by a mixture of filtering, averaging, and masking. The spectrum of these artifacts are broadband, but somewhat limited to frequencies below 100 MHz. Unfortunately, a long 'tail' of very low frequency was also evident that would not be able to be removed by the ~9 MHz low-pass filters used in one set of the electronics.

The ion bunch pattern of the RHIC accelerator includes an 'abort gap' of about 1 us duration where no beam signal is present. Since the electronics is usually timed to ignore samples acquired in this region, the timing of the switch control signal was adjusted such that the strongest part of the transient takes place within this gap. This alone prevented the strongest perturbations from affecting the position measurement.

In addition, a digital high-pass filter was implemented in the BPM electronics, centered around a 5 MHz cut-off frequency. This had the dual effect of both removing the low-frequency tail of the switch transient, and also removing other noise from sources in the accelerator complex.

Because of the high revolution frequency of the accelerator relative to the 1 Hz average measurement rate, the switching only needed to be performed about every 100 turns to still provide a stable signal when averaged down to a few Hz. This lower switching rate also had the benefit of reducing the overall impact of the transient on the running average, since the transient was only present for one out of every one hundred turns.

The combination of these techniques led to an almost complete removal of the transient effects of switching on the calculated BPM position.

CONCLUSION

The hardware required to realize the switching scheme described herein was relatively low in cost. The LEReC accelerator BPM system already had a requirement for amplifiers to be placed near the beamline, in order to improve the signal to noise ratio of the BPM signals at very low bunch intensity. A chassis and power supply were already necessary for these amplifiers, so adding the switching circuitry incurred a trivial cost.

Even in the case where there are no dynamic changes to the spectral content of the beam signal, BPM system designers usually strive to use well matched components in each of the sampling channels, especially in the filtering components. Procuring and testing these filters to verify their matching (usually in pairs) is a time consuming and sometimes a costly process. These costs of installing switching hardware should be compared to this in the sense that it relaxes the matching requirements for many of the circuit elements.

During the planning and design phase for LEReC, the idea of rapidly switching the BPM signals was extensively discussed [5]. This allowed ample time for experimentation and prototyping, which enabled us to develop a robust system and also allowed time to test the effects of both thermal drifts and signal shape on the position results, using simulated signals. It is sometimes difficult to determine the quality of BPM measurements in a real accelerator beam line, due to compounding uncertainties such as mechanical offsets, and dependence on data from other instrumentation systems about beam properties. Although many techniques such as beam based alignment can be used, the LEReC project had the unique quality that transverse cooling efficiency was closely related to the alignment of the interacting beams [1]. During the commissioning process of this experiment, it was shown that the switching of BPM signals was essential in providing the correct position measurements which then allowed transverse cooling to be optimized. The continual use of this technique then allowed long-term operational cooling [6] to take place over several months in order to achieve the RHIC low-energy experimental goals [7].

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