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LOW-COST BUTTON BPM SIGNAL PROCESSING ELECTRONICS FOR THE AWA ELECTRON LINAC*

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Abstract

Single-pulse, high dynamic range BPM signal detection has been at the top of the Argonne Wakefield Accelerator (AWA) Test Facility's most-wanted list for many years. The AWA beamline's unique capabilities require BPM instrumentation with an unprecedented dynamic range, making it challenging to design and prototype a cost-effective solution. We have prototyped many different approaches over the years. Finally, a recent prototype shows the long-sought solution for AWA's low-cost button BPM signal detection is becoming feasible. This paper shares the design and test results of this prototype.

INTRODUCTION

A Beam Position Monitor (BPM) is a device widely employed on accelerator beamlines worldwide, offering non-destructive insight into beam centroid information. With careful calibrations, it can also yield charge information from the signals. For certain applications, BPMs may even provide information on the temporal distribution of charged bunches. Researchers worldwide have extensively investigated various BPM configurations and published numerous review papers on their properties. Detailed and quantitative expressions of BPM properties can be found in these review papers [1–6]. Typically, a BPM system comprises a customized signal pick-up device and specialized processing electronics. The processing electronics are tailored to the BPM signals of the selected pickups, chosen based on the specific beam parameters of the facilities, and are typically costly.

AWA is a small accelerator research and beam test facility with limited budget and resources. Despite our constraints and recognizing the value of BPMs, we aim to maximize their installation on our beamlines. To meet this goal within our budgetary limitations, we have opted to develop our own BPM signal processing electronics.

As illustrated in Fig. 1, numerous locations along our beamline can benefit from the implementation of BPMs. Leveraging BPMs will enable us to monitor beam positions without relying on YAG screens, in turn giving us the opportunity to implement feedback control for beam stabilization and automatic tuning.

At present, AWA has one stripline BPM pickup installed on our drive beam line immediately after the final linac. This specific pickup was meticulously designed to optimize signal response at 1.3 GHz, corresponding to the L-band RF frequency of our RF system. The primary goal of this stripline BPM pickup is not only to acquire beam-position information but also to capture beam-phase data from the same pickup. Previously, we collaborated with Euclid TechLabs to develop the associated signal processing electronics, known as Euclid BPPM, with funding provided by the DoE 2009 SBIR Phase 1 project under Contract No. DE-SC0002513. While initial results were promising, the project unfortunately faced termination due to insufficient funding. We also have several commercial in-flange button-type BPM pickups purchased from MDC Vacuum Products®. These pickups are deployed on the various beamlines at AWA, including the ACT (Argonne Cathode Test Stand) beamline, the EEX (Emittance Exchange) beamline, and the Drive beamline. We have invested efforts into studying and characterizing the response of these button-type BPMs to our beam structure and preliminary work has been initiated to design the signal processing circuitry [7].

PREVIOUS EFFORTS

The previous efforts in BPM signal-detector design at the AWA facility have been documented numerous conference proceedings [8–10]. In Ref. [8], three distinct signal-detector design proposals were explored: an RLC resonator-based circuit, a half-wave rectifier with voltage-follower based circuit, and a modified peak-detector circuit. The results of bench tests and beam tests on these designs revealed promising output results for beam charge levels at or above 1 or 2 nC. However, they were found to be inadequate in producing meaningful results below these charge levels. Based on simulation studies, an active filter using 2n2222 was proposed in that paper.

In Ref. [9], we presented the prototyping results of two active filter prototypes, one utilizing the 2N2222 and the other employing the 2SC4083. The 2N2222-based active filter significantly elongated the BPM input signal to a FWHM width of approximately 3.5 microseconds. However, the peak amplitude of the output signal, as measured on the oscilloscope, was approximately 3 mV, falling short of the desired value for the incoming charge beam of approximately 2 nC. By comparison, the active filter prototype based on the 2SC4083 was capable of generating a signal 20 times stronger with only one third of the beam charge. For a 0.5 nC beam, the output from the prototype was 60 mV. While the

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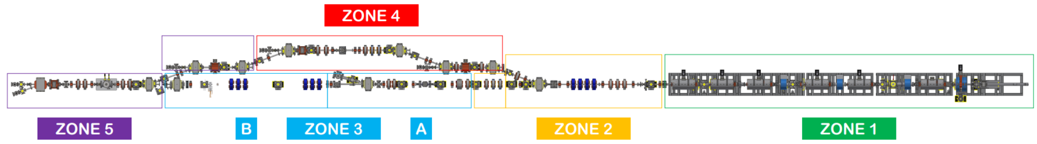

Figure 1: **AWA Beamline Layout.** With 6 dedicated device-under-test (DUT) areas in 4 experimental zones, AWA will benefit greatly from the opportunity to implement feedback-controls to stabilize and automatically tune the beam without needing destructive YAG screen diagnostics.

performance surpassed that of all other circuits tested, it still fell short of meeting our criteria for success.

In Ref. [10], we introduced an equivalent circuit model for the button BPM pickup, significantly enhancing the accuracy of our simulation studies. Additionally, we prototyped and simulated signal detectors using high-Q Band Pass Filters (BPFs) combined with envelope detectors. Based on simulation and prototype tests, it was determined that the high-Q BPF approach would only be effective for electron bunches with charges exceeding 1 nC. To address the detection of signals from MDC button BPMs excited with lower charge levels, we revisited the active filter approach. Using the results of simulation studies and assessments of previous active filter prototype results, we biased the first stage below cutoff. This adjustment resulted in a reasonably strong response for a MDC button BPM signal at approximately 300 mV.

Following the above prototype test, we attempted another active filter prototype utilizing the RF transistor BFU550, which boasted a significantly higher transition frequency. However, this prototype circuit proved to be exceedingly sensitive to RF noises emanating from our high-power RF stations, and thus we were unable to extract any meaningful signal from it.

We then reoptimized our active filter design based on the 2SC4083, incorporating a fixed bias network and implementing improved noise filtering on the power supplies. The new prototype and its test results are detailed in this paper, alongside the updated plan for our next steps.

THE UPDATED ACTIVE FILTER PROTOTYPE CIRCUIT AND TEST SETUP

In all our previous active filter prototypes, trim resistors were employed to facilitate adjustment of the bias network. While this practice offered flexibility in bias adjustment, the introduction of the equivalent circuit model in Ref. [10] has led to significantly enhanced accuracy in our simulation studies, eliminating the need for bias network adjustment during prototype tests.

As reported in Ref. [9], previous prototypes experienced relatively strong noises from the power supply. In this new prototype circuit, depicted in Fig. 2, efforts have been made to filter the power supply noises within the circuit. Additionally, a voltage follower constructed with AD8065 has been prototyped in this circuit to isolate downstream circuits or load conditions. To aid in troubleshooting, the circuit has been partitioned into two parts, allowing independent testing of the active filter and the voltage follower signal buffer.

Unlike our previous prototype tests, we have implemented upgrades to our data acquisition for enhanced precision. Rather than capturing images of scope traces on the oscilloscopes, we have programmed a virtual scope for the 16 GHz Tektronix oscilloscope. This enables us to capture the waveform of both the BPM raw signal and the output of the active filter, alongside the charge level measured using our ICT monitor program.

The signal connections remain largely unchanged from those described previously [10], except that attenuators and low-noise amplifiers (LNA) were not used to alter the input level of raw signals. Moreover, we have allocated dedicated beamline time for testing this prototype circuit, which allows us the opportunity to vary the MDC BPM signal level by adjusting the charge of the electron beam without affecting any ongoing experiments.

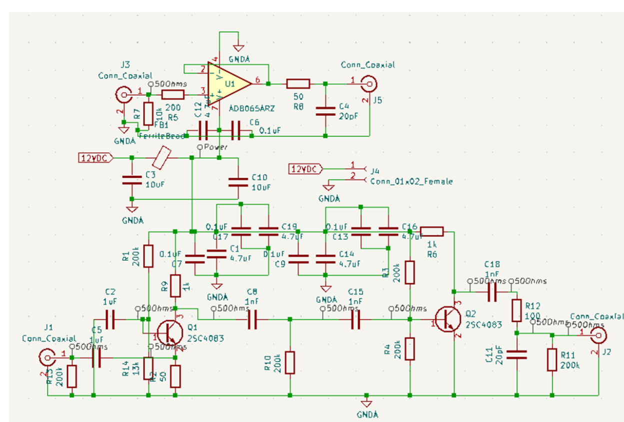

Figure 2: **Updated 2SC4083 based active filter.**

RESULTS OF THE PROTOTYPE TEST

Fig. 3a displays both the BPM raw signal and the response of the active filter prototype measured simultaneously on the same 16 GHz oscilloscope. Notably, the prototype circuit effectively converted the rapid MDC button BPM signal into a considerably slower signal, with a FWHM of approximately 20 to 25 ns.This measurement was conducted with the active filter output directly connected to the 50 Ω RF input of the 16 GHz oscilloscope, and it was anticipated that the response will be further improved when the active filter is isolated using the voltage follower.

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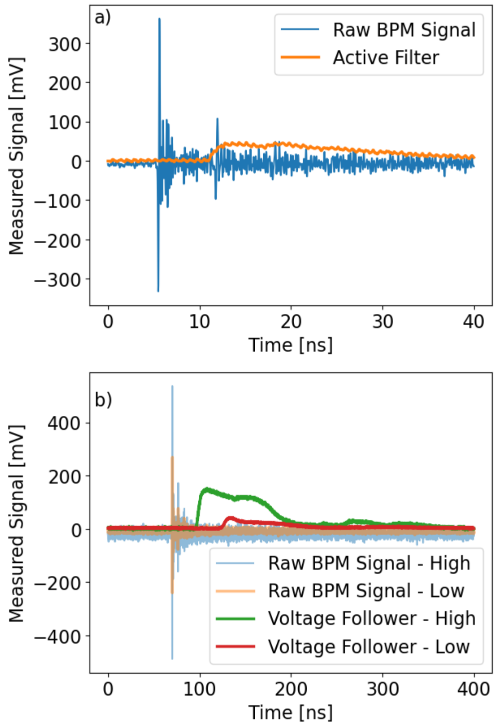

Figure 3: **Prototype Tests.** We show the results of the circuit testing with **a)** just the active filter and **b)** the voltage divider circuit intended to further slow the signal.

We routed the active filter output signal through the voltage follower on the prototype circuit board and repeated the measurement. As anticipated, and as depicted in Fig. 3b, we observed a much stronger signal with a longer pulse length of approximately 70 ns FWHM for a similar input signal level.

Also shown in Fig. 3b, the prototype response is even sensitive to raw BPM signals of approximately 200 mV. Based on our previous measurements, we estimate that the MDC button BPM can generate a signal of around 3 mV/pC, suggesting that a signal level of 200 mV corresponds to a beam charge level of approximately 70 pC. From this observation, we conclude that this prototyped BPM signal detector is capable of functioning effectively with MDC button BPMs at beam charge levels of 70 pC and above. Furthermore, as demonstrated in our previous work [10], we have shown that we can amplify raw BPM signals as small as a few mV to 300 mV using LNAs. With the use of LNA pre-amplifiers, we can extend the sensitivity of our signal detector down to a few pC.

NEXT STEPS

The next step is to work on digitizing the signal for use in tuning and controlling the beamline parameters. Building a FPGA-based digitizing circuit operating at 100 MSPS appears to be the most cost-effective solution given the number of monitors we wish to install, however it has not proven to be effective for the signals from the current prototype

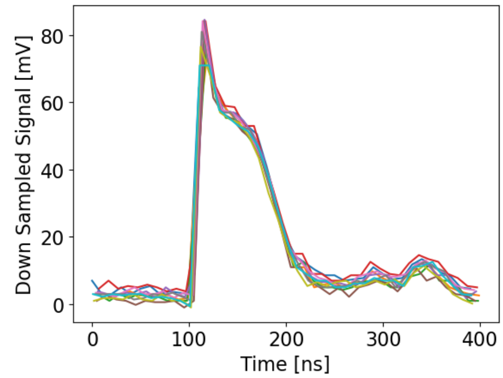

Figure 4: **Sampling Rate Issues.** One BPM signal detector output signal artificially down sampled at 100 MSPS with sampling clock at different phases.

of the BPM signal detector. As demonstrated in Fig. 4, when compared to the signal captured with the 16 GHz oscilloscope, the down-sampled results at 100 MSPS exhibit jitter exceeding 10% across different phases of the sampling clock. Increasing the digitization rate to 1 GSPS or higher would mitigate this issue but will likely increase the cost significantly to a point that it is no longer affordable for AWA.

To ensure the final product is actually low cost, we need to slow the signal down further with a customized peak detector circuit. Using LTSpice from Analog Device [11], we designed a peak detector that can further slow the signal down to easily allow us to use ADCs at 10-20 MSPS.

Naturally, our next step will be building and testing a prototype circuit with this customized peak detector. Meanwhile, we will also working on the design of the digitizing electronics.

CONCLUSION

It is quite a challenge to design and prototype a cost effective solution for single pulse, high dynamic range button BPM pickup signal detector circuits. After many iterations we are finally closing in on our target BPM circuit design. Our next steps are to test the total circuit design with an added peak detector circuit, as well as work on digitizing the signals to be collected while running. From there, we will continue our work on feedback mechanisms for keeping the beam aligned without needing to check destructive YAG screen diagnostics.

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