ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-TUPA28

UPDATE ON THE DEVELOPMENT OF A LOW-COST BUTTON BPM SIGNAL DETECTOR AT AWA*

W. Liu†, C. Whiteford, D. S. Doran, E. E. Wisniewski, G. Chen, J. G. Power, P. Piot, S. Kim, X. Lu
High Energy Physics Division, Argonne National Laboratory, Lemont, IL, USA

Abstract

Single-pulse high dynamic range BPM signal detector has been on the most wanted list of Argonne Wakefield Accelerator (AWA) Test Facility for many years. Unique capabilities of the AWA beamline require BPM instrumentation with an unprecedented dynamic range, thus cost-effective solution could be challenging to design and prototype. Our most recent design, and the results of our quest for a solution, are shared in this paper.

INTRODUCTION

Beam position monitor is a device widely used on accelerator beamlines worldwide. It can provide information on beam centroid nondestructively. One can also obtain charge information from the signals with careful calibrations. For some applications, BPM might even provide the temporal distribution information of charged bunch. Researchers around the world have studied the properties of many different BPM configuration in detail and published many review papers. For detail and quantitative expression on the BPM properties, one can find them in those review papers [1-6]. As presented in the references, a typical BPM system consists of a customized signal pick-up device and specialized processing electronics. The processing electronics are usually specialized to the BPM signals of the specific pickups chosen based on the specific beam parameters of the specific facilities and are usually expensive.

AWA is a small accelerator research facility which has limited budget and resources. But since BPM is such a wonderful device, we would like to install them as many as possible on our beamlines. In order to fulfill our need with our limited budget and resources, we decided to design our own BPM signal processing electronics.

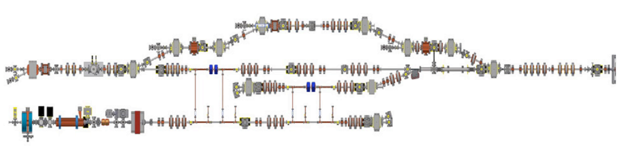


Figure 1: AWA beamline layout.

As shown in Fig. 1, there are many places on our beamline that can use the help of BPMs. With the help from BPMs, we will be able to monitor the beam positions on the beamline without using YAG screens, which gives us the opportunity to use feedback-control to stabilize and automatically tune the beam.

Currently at AWA, we have one stripline BPM pickup installed on our drive beam line right after the last linac. This stripline BPM pickup was specially designed to maximize the signal response at 1.3 GHz, the L-band RF frequency of our RF system. The objective of this stripline BPM pickup is to enable us not only to obtain beam-position information but to obtain beam-phase information as well. We previously worked with Euclid TechLabs to develop such signal processing electronics, called Euclid BPPM funded by DoE 2009 SBIR Phase1 project under Contract # DE-SC0002513. The results were very promising but the project was cutoff due to lack of funding.

We also have few commercial in-flange button-type BPM pickups purchased from MDC Vacuum Products®. One is installed on our ACT (Argonne Cathode Test Stand) beamline, one on our EEX (Emittance Exchange) beamline and one on our Drive beamline. Some efforts were put into studying and characterizing the response of these button-type BPMs to our beam structure. Some preliminary efforts were also put into designing the signal processing circuitry [7].

Previous BPM signal-detector design efforts at AWA facility have been discussed in Refs. [8, 9]. In Ref. [8], three separate signal-detector design proposals were examined (RLC resonator-based circuit, half-wave rectifier with voltage-follower based circuit and modified peak-detector circuit). The final bench test and beam test results on those designs indicated that they were able to produce promising output results for beam charge-levels at or above 1 or 2 nC but were unsatisfactory in producing any meaningful results below those levels of charge. Based on some simulation studies, active filter using 2N2222 was proposed in that paper.

In Ref. [9], we presented the prototyping results of two active filter prototypes, one was using 2N2222 and another one was using 2SC4083. The 2N2222-based active-filter stretched out the BPM input-signal significantly to a FWHM width of approximately 3.5 ms. The peak-amplitude of the output-signal, as measured on the oscilloscope, was approximately 3 mV, a less-than-desired value for the incoming charge-beam of the experiment that had a charge-level of approximately 2 nC.

As reported in Ref. [9], the 2SC4083 based active filter prototype, comparing with the 2N2222 based prototype, can generate 20 times stronger output signal with only one third of the beam charge. For 0.5 nC beam, the output from the prototype was 60 mV. The performance was better than all other circuits we have tested, but it is still not good enough to declare the success. Search for the solution continues.

*Work supported by DOE Office of HEP and Office of BES.
† wmliu@anl.gov

ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-TUPA28

EQUIVALENT CIRCUIT MODEL FOR BUTTON BPM PICKUP

During the beam test of the two active filter prototypes, it was noticed that the actual measured results were much smaller than predicted with circuit simulations. It was basically telling us that our simulated input signal source has frequency contents that doesn't exist in the real button BPM pickup signals, and we need a more accurate signal source for the simulations. After some research, we came up with an equivalent circuit model for the button BPM pickup.

As showing in Fig. 2, the model consists of a transmission line coupled with a current loop using a small capacitor. A gaussian current pulse running in the current loop will generate a signal looks very similar to the button BPM pickup signal seeing on oscilloscopes with 16 GHz or higher frequency bandwidth.

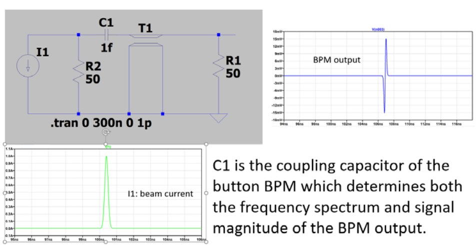


Figure 2: Equivalent circuit model of button BPM.

HIGH Q BPF + ENVELOPE DETECTOR

Even though the 2SC4083 based active filter allowed us to stretch the button BPM pickup signal from about 0.5 nC beam. It is still far from our goal, the pC charge level. And thus, we started thinking about using high Q BPF + envelope detector as what is used in our BPPM project.

To verify the feasibility, we applied a commercial BPF with passband between 63 MHz to 85 MHz to button BPM output from about 30 nC charge. The filter output was captured using oscilloscope. The result is presented in Fig. 3.

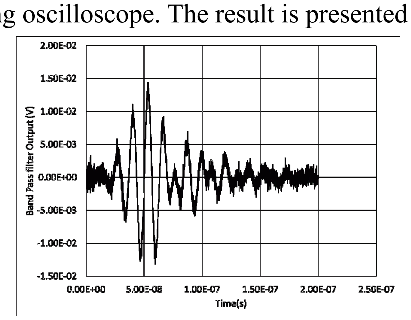


Figure 3: BPF (65 MHz to 85 MHz) output of button BPM signal from 30 nC electron bunch.

We also did circuit simulation using the band-pass filter model and our new BPM signal source model. As showing in Fig. 4, the simulation has predicted an output with similar temporal structure as the measurement. For an input signal of about 50 mV, the BPF was generating an output signal of about 18 µV. The ratio between input and output is about 2778 to 1. For the BPF measured results, using our knowledge on our button BPM and signal loss on the helix

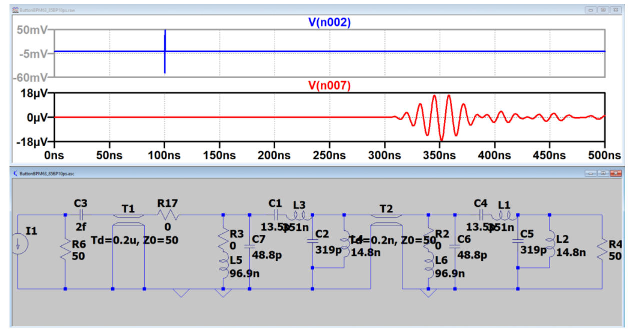


Figure 4: BPF simulation results of BPM signal.

cable passing the signal back to control room from the pickup, the input and output ratio is estimated to be about 1467 to 1.

Based on the above estimation, this approach would work for high charge beam for sure. For beam charge less than 1 nC, the output will be mini-volts and under, and we will have trouble in dealing with them in a noisy environment. As it is impractical for us to amplify the button BPM pickup signal beyond few volts, this high Q BPF combined with envelope detector is not a solution for us.

REVISITING ACTIVE FILTER

With the high Q BPF attempts hitting the wall, active filter seems to be our only hope for cost-effective solution.

After reviewing the prototype test results, we realized that choosing 2N2222 was a mistake. Even through the frequency contents we are aiming for is smaller than its transition frequency. It acts like a low pass filter + amplifier to the BPM pickup signal which will sure miss our unpronounced goal, utilizing the saturation to produce extra frequency components which requires amplifier comes in first. We also realized that pushing the work point to near saturation is not a good choice. We might be able to set the work point to where DC current near its max limited by the power supply and collector resistance, but AC currents can still be supplied by the capacitors connecting to collector. So instead, we should be aiming for biasing 1st stage to near cutoff.

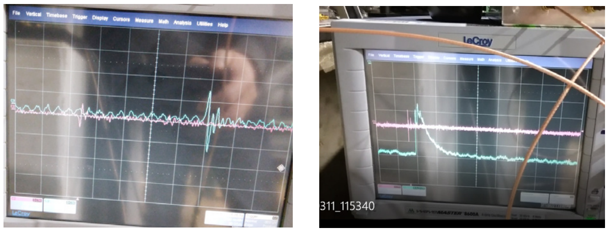
2SC4083 Based Active Filter Retest

Based on our assessments on the active filter beam test results, we adjusted the bias of the 1st stage on 2SC4083 based active filter to near cutoff and did the beam test again.

During the test, we split the button BPM pickup signal 50/50 with one branch directly sent into oscilloscope and use it as a trigger. The other branch went through our test setup.

We first attenuate the signal down to about 10 mV, and then use multiple LNA stages to amplify the signal back into about 300 mV. As showing in Fig. 5, both signal and noises got amplified by the LNAs. This signal is then connected into the 2SC4083 based active filter. As showing in Fig. 5, with the 1st stage biased slightly into cutoff, class C amplifier, a reasonably strong and clean output signal was obtained.

5th North American Particle Accel. Conf. NAPAC2022, Albuquerque, NM, USA JACoW Publishing
ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-TUPA28



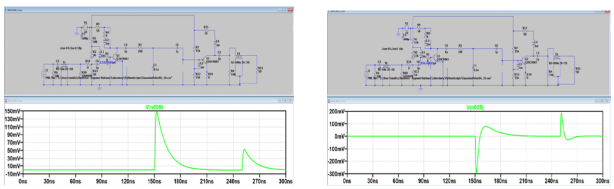
(a) (b)

Figure 5: (a) Scope trace showing amplification of attenuated BPM signal; (b) scope trace showing active filter output and input signal.

Simulation Studies

Using our new signal source model, we did a lot of simulation studies using LTSpice from Analog [10].

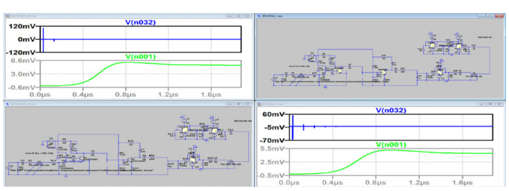
Simulation shows that active filter with Class C in first stage works better than Class A on both stages, as shown in Fig. 6.



(a) (b)

Figure 6: (a) Simulation with Class C + Class A amplifier; (b) simulation with Class A on both stages.

Based on simulation studies results, in our next prototype, we will replace 2SC4083 with BFU550 to improve the sensitivity. As showing in Fig. 7, using BFU550 can extend the lower end of input dynamic range from about 120 mV to about 70 mV. We have also made many other changes to the active filter design based on simulations.



(a) (b)

Figure 7: (a) Active filter using 2SC4083; (b) active filter using BFU550A. Both circuits have the same voltage buffer and peak detector.

Plan for Next Prototype

As indicated in simulation results, the input dynamic range of the active filter is from about 70 mV to about 6 V. To use it with button BPMs at AWA, we will need to attenuate the BPM pickup signals when operating with a high charge beam or amplify the BPM pickup signals when operating with a low charge beam. As showing in Fig. 8, a RF switchyard has been designed and will be prototyped to confirm the performance. The RF switchyard will allow us to set gains using TTL level signals to choose among 60 dB, 40 dB, 20 dB, 0 dB, -10 dB, -20 dB, -30 dB and -40 dB.

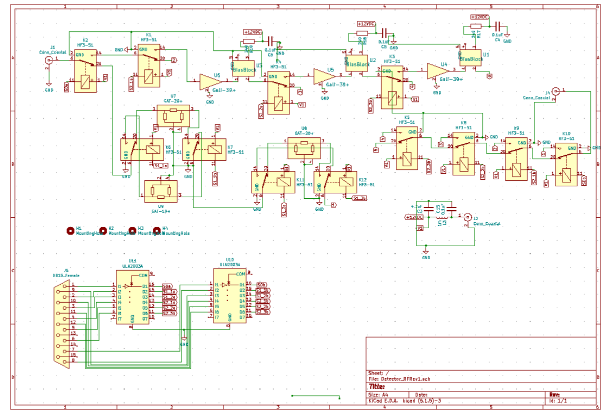


Figure 8: Schematics of RF switchyard.

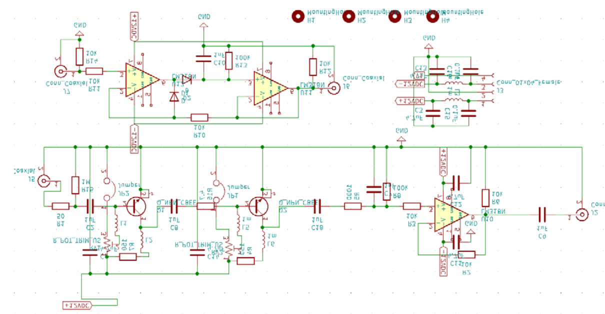


Figure 9: Schematics of active filter using BFU550 and signal buffer + peak detector (bottom).

As showing in the simulations, the active filter will generate output signal with about 15 ns FWHM, it needs to be further stretched out to allow it to be digitized with low-speed ADCs. As showing in Fig. 9, voltage buffer and peak detector are added to the schematics and will be tested together with the active filter.

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. We have been working on this on and off for many years and finally came across the likely solution. Hopefully, the upcoming prototype test will answer all the remaining questions and end the search.

REFERENCES

[1] Beam Position Monitors, `http://apps.fz-juelich.de/pax/pages/2/2c/Cas_bpm_main.pdf`

[2] R. E. Shafer, "Beam position monitoring," *AIP Conf. Proc.*, vol. 212, p. 26, 1990. doi:10.1063/1.39710

[3] S. R. Smith, "Beam Position Monitor Engineering," *AIP Conf. Proc.*, vol. 390, p. 50, 1997. doi:10.1063/1.52306

[4] G. R. Lambertson, "Electromagnetic Detectors," *Lect. Notes Phys.*, vol. 343, p. 380, 1988. DOI: 10.1007/BFb0018297

[5] J. M. Byrd, "Bunched Beam Signals in the Time and Frequency Domain," in *Beam Measurement*, Singapore: World Scientific, 1999, pp. 233-262.

ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-TUPA28

[6] J. Hinkson, "Advanced Light Source Beam Position Monitor," *AIP Conf. Proc.*, vol. 252, p. 21, 1992. doi:10.1063/1.42119

[7] C.-J. Jing, J. G. Power, J. H. Shao, and C. Yin, "A Low Cost Beam Position Monitor System", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 1961-1963. doi:10.18429/JACoW-IPAC2018-WEPAF059

[8] W. Liu et al., "Update on BPM Signal Processing Circuitry Development at AWA", in Proc. NAPAC'19, Lansing, MI, USA, Sep. 2019, pp. 919-922. doi:10.18429/JACoW-NAPAC2019-THXBA4

[9] E. M. Siebert et al., "The Development of Single Pulse High Dynamic Range BPM Signal Detector Design at AWA", in Proc. IPAC'21, Campinas, Brazil, May 2021, pp. 909-911. doi:10.18429/JACoW-IPAC2021-MOPAB287

[10] LTspice Simulator | Analog Devices, https://www.analog.com