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DESIGN AND EXPECTED PERFORMANCE OF THE NEW BPM SYSTEMS FOR AWAKE RUN 2c

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Abstract

The AWAKE facility at CERN uses novel proton beam-driven plasma wakefields to accelerate electron bunches over a 10 m plasma source. The facility will soon be rebuilt to study methods to improve the quality of the accelerated electron beam, requiring better resolution from the proton beam position monitors (BPMs). In addition, it is desirable to replace the existing bespoke electron BPMs with an in-house solution. Both upgrades will reuse the existing BPM pickups (electrostatic buttons and striplines, respectively) but replace the electronic front-ends and control system interfaces. An RFSoC-based BPM front-end is concurrently being developed for the HL-LHC upgrade, which, if appropriate for AWAKE, would reduce production and maintenance efforts. For the proton BPMs, distributed along an 800 m transfer line, time-multiplexing of both pickups per plane has been chosen both to reduce cabling and channel count and improve systematic errors in the measurements. We present the expected performance of both the AWAKE proton and electron BPMs using the prototype HL-LHC BPM front-end, based on measurements from the existing facility.

INTRODUCTION

The Advanced Wakefield Experiment (AWAKE) facility at CERN has now entered a long shutdown to rebuild the beamline ahead of the Run 2c phase of the project [1]. As part of the beam instrumentation upgrades to measure the lower emittance beams, the acquisition electronics for the beam position monitors (BPMs) of both the proton beamline and the electron beamline will be upgraded. Additional complete BPMs will be provided for a second electron beamline to deliver dedicated witness bunches for acceleration. The Run 2c layout is shown in Fig. 1.

The existing proton BPMs reuse 60 mm button pickups (see Fig. 2a) from the LEP collider that feed local digitisers based on narrowband filtering and demodulating logarithmic amplifiers. The acquisition electronics were a prototype for the ALPS system, later installed in the SPS [2, 3]. This system achieves an average 70 µm of noise-limited resolution, which the project would like to reduce to 20 µm with the upgrade.

For the electron BPMs, stripline pickups and custom acquisition electronics were contributed by TRIUMF who were then a member of the AWAKE collaboration. The striplines are of two apertures: 40 mm for the electron beamline, shown in Fig. 2b, and 60 mm after the merging point with the protons. Similar to the proton BPMs, the acquisition electronics also use narrowband filtering, but downconvert and sample the signal instead of demodulating it [4, 5]. Although the existing best-case noise-limited resolution of 10 µm meets the requirements for Run 2c, it is no longer feasible to acquire further BPMs from TRIUMF and so both the new units and replacements for existing BPMs will be produced at CERN. This will provide a single in-house source and reduce future maintenance effort.

Concurrently with the AWAKE Run 2c design work, the HL-LHC BPM project began designing wideband direct-sampling acquisition electronics based around the Zynq Ul-

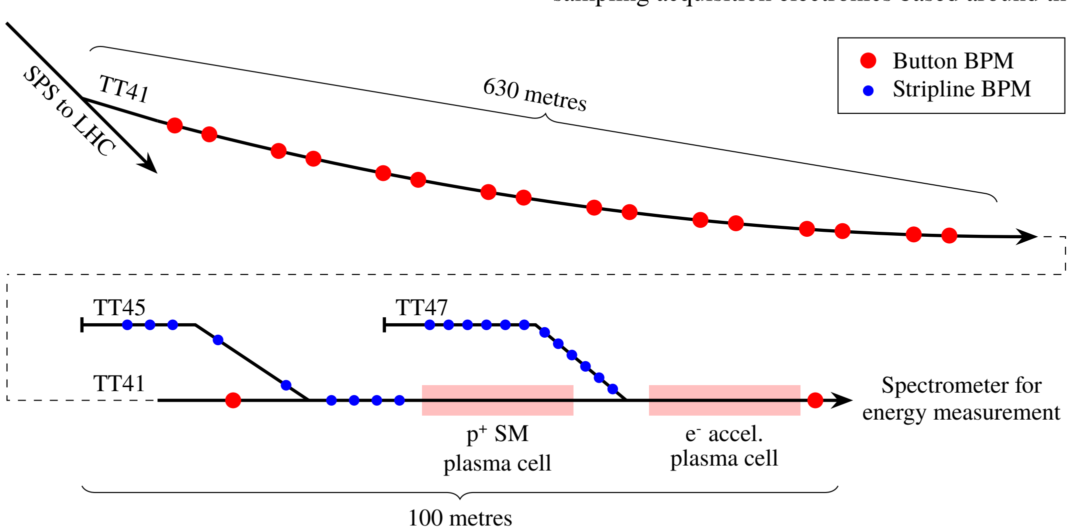

Figure 1: The AWAKE layout for Run 2c. TT47 and the plasma chamber downstream will be added for this run.

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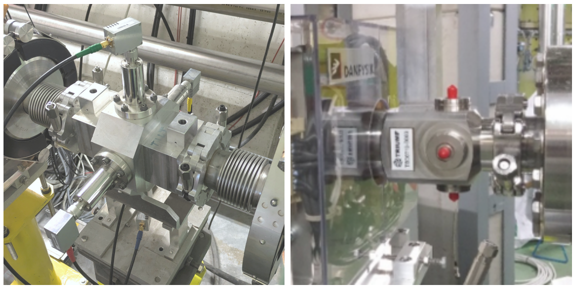

(a) LEP button. (b) TRIUMF 40 mm stripline.

Figure 2: AWAKE beam position monitor pickups.

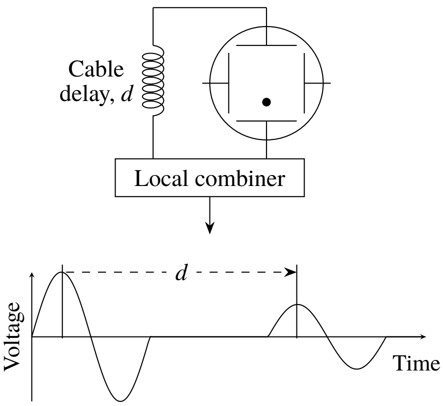

Figure 3: Time-division multiplex technique applied to opposite electrodes on a pickup plane.

traScale+ RFSoC [6]. This can provide 8 channels of 14-bit ADCs with 5 GSps sampling rate. It was therefore proposed that the AWAKE Run 2c electronics be based on the HL-LHC design, with modelling and measurements at the existing facility used to verify the performance and determine whether any changes are required.

SYSTEM DESIGN

Time-Division Multiplexing

The combination of the proposed wideband sampling and the single-bunch nature of the experiment (with the fastest bunch repetition at 10 Hz for a maximum 1 ns bunch) means it is possible to use time-division multiplexing to reduce both the channel count and the systematic errors per plane due to drifts in cable and component transfer characteristic. An illustration of the technique is shown in Fig. 3. From simulation and measurements a suitable cable delay has been found to be 15 ns (3.3 m). Multiplexing of more than two electrodes is possible but care must be taken to avoid crosstalk between pulses due to any reflections. We have chosen a 2:1 multiplex to simplify this and because it suits the cable layout and available channel count.

HL-LHC BPM Electronics

The input stage for the proposed HL-LHC BPM acquisition electronics under prototype is shown in Fig. 4. The design includes 60 dB of switchable gain, from −40 dB to

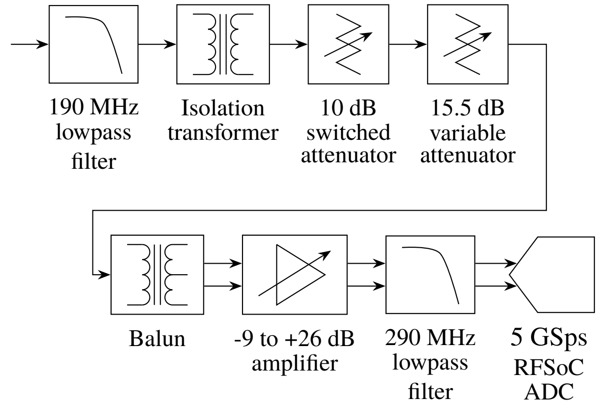

Figure 4: HL-LHC BPM input RF signal path. Does not include calibration output via crossbar switch located before this signal path.

+20 dB. Calculations based on measurements at AWAKE have shown that this will cover the full range of expected amplitudes from both the button and stripline pickups, for both the planned proton and electron bunches. The heart of the acquisition system is the AMD Zynq™ Ultrascale+™ XCZU47DR RFSoC [7], provided as a system-on-module from a commercial supplier, with a carrier board being developed by CERN and scheduled for production in 2026.

Processing for AWAKE

Software processing for the bunch signals will be straightforward and consists of:

1. Windowing of time multiplexed pulses.
2. RMS power calculation.
3. Position calculation using sensitivity function.

The system is designed to self-trigger but can also accept an external trigger if required.

PREDICTED PERFORMANCE

Physical models of the pickups were created in CST Microwave Studio and the pickup voltages generated by the wakefield simulation were then propagated through noisy models of the cabling, front-end and ADC written in Python. The simulated sampled pulses were then windowed and the RMS power of each electrode used to obtain the position by log-ratio with a 5th-order polynomial fit for the sensitivity function. Both analytical and Monte Carlo error propagations were performed and showed good agreement ($\ll 1\,\%$). A comparison of the simulated and later measured proton bunch signals through the button BPM and front-end filtering, shown in Fig. 5, demonstrates that the sample rate is sufficiently high for wideband sampling of these bunches and that the simulation is suitable for predicting the system performance.

Measurements of a prototype front-end with the candidate filters and ADC was made possible using the Run 2b BPMs and particle beams. For the proton beam, we could not take sufficient data for statistical analysis, so individual measured pulses were propagated through the simulation noise models

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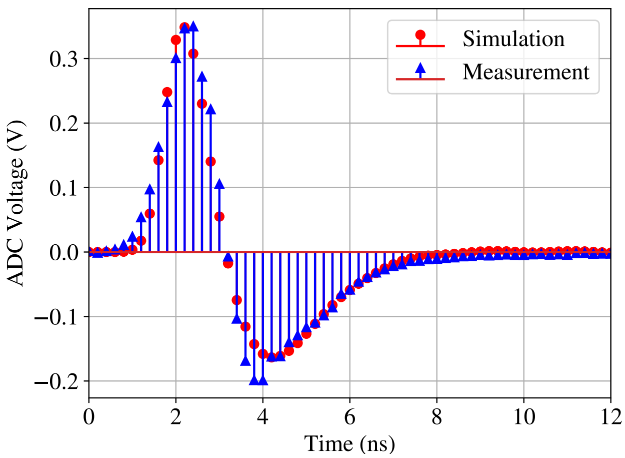

Figure 5: ADC samples with optimal front-end gain (70 % of 1 Vpp ADC full-scale range) from CST simulation (red) and real measurements (blue) of a 1 ns proton bunch through the button BPM.

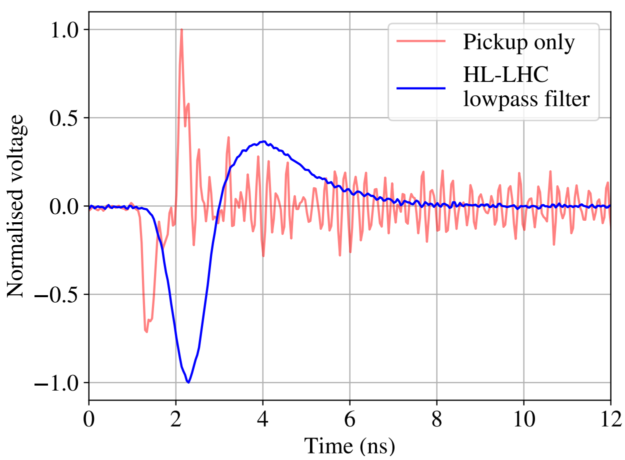

Figure 6: A stripline BPM oscilloscope measurement showing a 4 ps 600 pC electron bunch both with (red) and without (blue) the HL-LHC 190 MHz lowpass filter.

to predict the achievable position error. These results are shown in Table 1. The performance is given for the front-end optimised for the highest bunch charge, 4.8 nC (3×10^{11} protons). There is sufficient switchable gain and attenuation to optimise for the entire range of bunch charges, so a software feature will allow a gain auto-range action when requested by the operator. This will reduce the predicted position noise for lower charge bunches towards the 10 µm best case, depending on the granularity of the gain ranges. Sufficient protection will be provided on the HL-LHC front-end to protect the inputs across expected extremes of the signal amplitude range.

For the electron BPM, we could perform both a statistical analysis and compare the results with a simultaneous measurement using the legacy TRIUMF system. Beam motion was removed from this statistical sampling by splitting a single pickup to feed both inputs for a single plane on the front-ends. One vertical plane pickup fed the prototype

Table 1: Predicted Position Errors Due to Noise for the AWAKE Proton BPM Based on Prototype Measurements and Simulation

Bunch Charge (nC)	RMS Position Error (µm)
4.8	10
1.6	30
0.8 (pilot)	600

Table 2: Predicted Position Errors for 60 mm Stripline Due to Noise for the AWAKE Electron BPM Based on Prototype Measurements

Bunch Charge (pC)	RMS Position Error (µm)	
	Prototype	Legacy
425	20 (15*)	30 (20*)
132	52 (35*)	88 (59*)

*Scaled for 40 mm striplines.

and the other fed the legacy system. An interesting discovery was strong resonant modes due to stripline geometry which risked aliasing problems with the wideband sampling, but the HL-LHC lowpass filter reduces these sufficiently as shown in Fig. 6. Results for the electron stripline BPM measurements are shown in Table 2.

The electron BPMs will also have an auto-range provision, improving the error at lower bunch charges. For the lowest required bunch charge of 100 pC, the available system gain is at the limit of the amplifiers, so there is no real improvement on the error shown in the table. However, it is shown from our side-by-side measurement that this error is lower than the existing system and the requirement was to match it. Additional gain margin could be found by removing the 5 dB of multiplexer loss, but this would introduce systematic error from cable and front-end drift.

CONCLUSION

The proposed HL-LHC RFSoC wideband sampling electronics have demonstrated sufficient performance to achieve the required position error specification for the AWAKE Run 2c BPMs without modification. This provides the best result for production, maintenance and spares management which is a priority for future systems.

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