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THE INSTALLATION AND COMMISSIONING OF THE AWAKE STRIPLINE BPM*

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ABSTRACT

AWAKE (The Advanced Proton Driven Plasma Wakefield Acceleration Experiment at CERN) stripline BPMs are required to measure the position of the single electron bunch to a position resolution of less than 10 µm rms for electron charge of 100 pC to 1 nC. This paper describes the design, installation and commissioning of a such BPM system developed by TRIUMF (Canada). Total 12 BPMs and electronics had been installed on AWAKE beam lines and started commissioning since Fall of 2017. The calibration and measurement performance are also reviewed.

SYSTEM OVERVIEW

AWAKE facility is a proof-of-principle R&D experiment at CERN and the world's first proton driven plasma Wakefield acceleration experiment [1]. Its construction has been completed and the commissioning has been started since Fall of 2017, which includes the stripline BPMs for tuning the electron beam. Refer to Fig. 1 for the layout of the AWAKE electron beamline and the common beamline, the electron BPMs locations and other diagnostic devices.

A total 12 BPMs have been installed on the AWAKE, with 6 on the electron beamline, and 6 on the common beamline. Those on the electron beamline are 40 mm aperture, while those on the common beamline are 60 mm aperture. They both have coverage angle of 38 degree, and with longitudinal length of 120 mm and 124 mm. Because of these parameters, their sensitivities are supposed to be slightly different. The processing electronics, i.e. BPM DSP (Digital Signal Processor), is in the hall way which has about 30 ~ 60 meters to the BPMs. The radiation dose rate level there is low enough that the electronics is not designed to be radiation hard. Refer to Fig. 2 for the system diagram, which describes the electronics, network and data acquisition computer. All the BPM DSPs are powered through the power bars that support Ethernet interface, which allows the DSP boxes to be power cycled in the situation that the communication becomes dead. Such situation happened several times during the commissioning, this remote reset scheme prevented human access to the site which is difficult or impossible during SPS operation. Besides the FEC (Front End Computer) which runs the DAQ software FESA server (FESA: What also is shown in the diagram is the triggers which signal the presence of the electron or proton beam bunches.

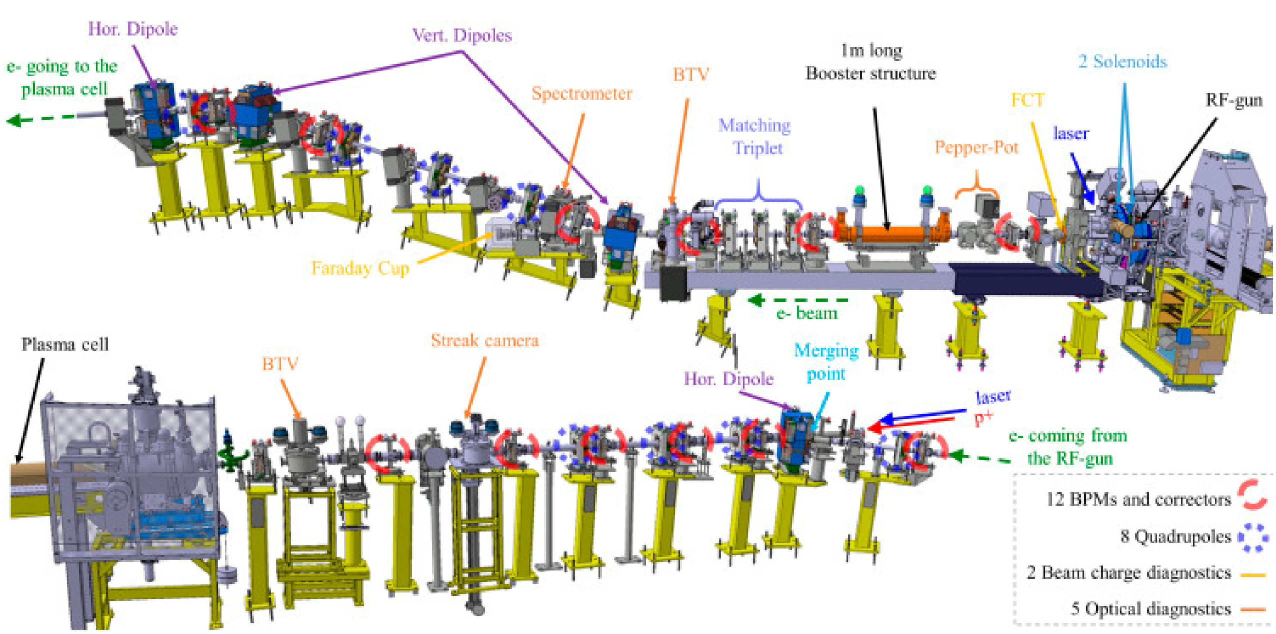

Figure 1: AWAKE beam lines and BPM locations.

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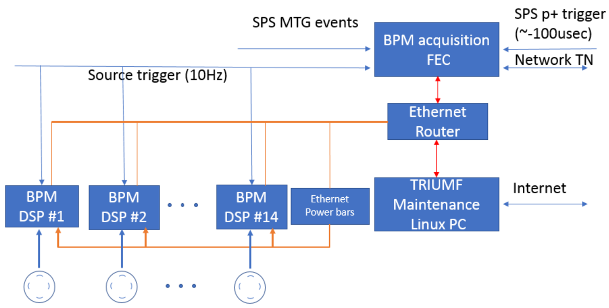

Figure 2: AWAKE stripline BPMs: electronics, triggers, DAQ, and Maintenance computers.

The system so far has been working with self-trigger mode, which continuously detect the beam pulse and trigger itself for event processing. The Fig. 3 shows an installed 40 mm BPM installed on the electron beamline, with the four antenna cables not yet connected.

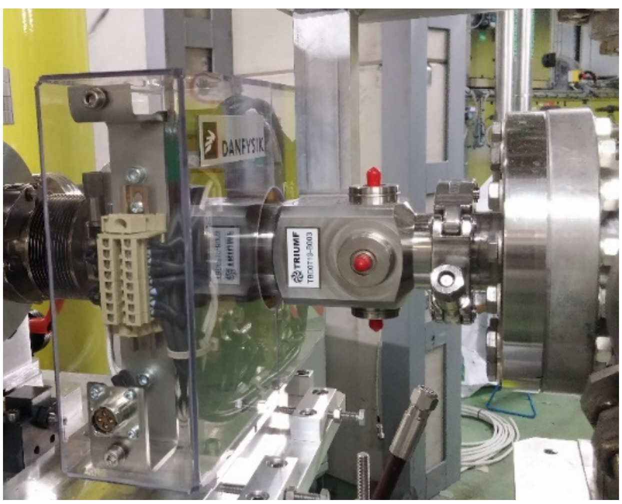

Figure 3: 40 mm AWAKE stripline BPM on the electron beam line.

The Fig. 4 is the BPM DSP rack, total 14 DSP boxes and one LO source, one calibration source are installed in the rack. Low loss BPM signal RF cables are routed to the back of the DSP rack, and then extended with thinner semi-rigid RF cables to reach to the input SMA connectors located on the front panels of the 1U DSP boxes. For the BPMs mounted on the common beam line, there is a customize designed Mini-Circuit high power band pass filter for each BPM signal to prevent the sensitive front end electronics to be damaged by the much stronger proton bunch signals.

BPM ELECTRONICS

The single electron pulse's horizontal/vertical position and intensity could be calculated from the signals induced on the four BPM antennas by that electron pulse. To the first order approximation, the position X or Y could be calculated as X = S * Diff/Sum, with Diff/Sum is the ratio of the signal difference over signal summing from the two opposite electrodes, and S as the sensitivity constant [2]. On the AFE board (Analog Front End), the four signals are band pass filtered, frequency down converted and amplified, and then digitized by a 16-bit flash ADC at 100MSPS on the digitizer board. On the FPGA board, A Xilinx SPARTAN6 processes the waveforms to get the position and intensity information, and pack them into an event data. The FESA server running on the FEC readout the event packets from each DSP module at a frequency of about 10 Hz, and publish the data to client software when requested on the local technology network. Refer to Fig. 5 for the hardware electronics, three boards: AFE, Digitizer and FPGA board are integrated into a 1U crate, named BPM DSP 1030, are stacked on the standard 19 inches rack. Each DSP module receives four antenna signals from one BPM, and a trigger signal. The TTL trigger signal multi-dropped at each DSP and terminated with 50 ohm at the last DSP module. Also there is one LO (Local oscillator source) input to receive the 434MHz LO signal for the frequency mixer, and calibration input to receive an ultra-fast pulse for drift calibration purpose. At self-trigger mode, the DSP module runs at the full speed clock, and consumes more than 20 watts, thus four +12V DC fans are equipped on the back panel to keep the inside temperature low. The detailed design of the AFE, Digitizer and FPGA firmware has been described in a previous paper [3].

Figure 4: BPM DSP rack and TRIUMF Linux PC.

Figure 5: BPM DSP 1030 module inside: AFE, digitizer, FPGA board.

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CALIBRATION

The calibration of the BPM system involved two types of offset errors, one is related to the electronics channel inside DSP module, and another one is the offset introduced by the BPM mechanical tolerance, unbalanced cable/connectors.

The first one was performed with an ultra-fast pulse generator (AVTECH AVM-2, amplitude 15.6V, FWHM 250 ps), connected to a 1:4 wide band RF power splitter and then fed to the four inputs of the DSP module. The channel gain parameters were adjusted to zero any position offset. Since the first attenuator (Digital Attenuator) in the AFE is a single channel type and its gain value varies from chip to chip slightly, the above calibration procedure needs to be performed on each of the three attenuator gain settings: 0, -10 -20 dB. For the same reason, the other gain setting on the digital attenuator should not be used since they are not calibrated. The second attenuator in the VGA (Variable Gain Amplifier) on the AFE has two channels on the same die and does not suffer this issue.

The second one is defined as Skew parameter in the FPGA firmware and stay unchanged with the associated BPM and its cables. In Table 1, the 40 mm BPM calibration data are listed. The first part is the offset due to the BPM mechanical tolerance and was measured in house at TRIUMF before shipped to CERN. The second part is the offset due to the cable/connectors and measured on site after the installation. The two offset parts are multiplied to get the Skew factors, which are to be applied to each measured. The procedure was to use the same AVTECH pulse generator as above, to drive one of the four BPM antennas, and measure the position offset from the opposite plane.

Table 1: 40 mm BPM Static SKEW Calibration Data

Electronics module #	4	0	1	7	6	5	2
Monitor #	2	3	4	5	6	7	10
Offset, a-c plane, mm	-0.069	0.067	0.07	-0.22	0.028	0.059	0.086
Offset, b-d plane, mm	0.019	-0.035	-0.025	0.047	-0.042	-0.053	0.018
ratio value a/c	0.9866	1.0132	1.0138	0.9579	1.0055	1.0116	1.0170
ratio value b/d	1.0037	0.9932	0.9951	1.0092	0.9918	0.9897	1.0035
cable offset a-c plane, um	40	25	35	-90	-40	26	0
cable offset b-d plane, um	80	180	-10	-160	150	400	-43
ratio value a/c	1.0053	1.0033	1.0047	0.9881	0.9920	1.0035	1.0000
ration value b/d	1.0107	1.0243	0.9987	0.9789	1.0305	1.0548	0.9943
accumulated ratio a-c	0.991864	1.016581	1.018535	0.946435	0.997483	1.015126	1.016972
accumulated ratio b-d	1.014489	1.0173	0.993794	0.987937	1.022022	1.043911	0.997792
SKEW a-c	1.0082	0.9837	0.9818	1.0566	1.0025	0.9851	0.9833
SKEW b-d	0.9857	0.9830	1.0062	1.0122	0.9785	0.9579	1.0022

There is another calibration situation for the dynamic offset error (drift) due to temperature fluctuation, this is to be compensated with a calibration pulse input on the front panel of the DSP. This pulse could be turned on when there is no beam operation, and X, Y position offset could be checked along the long period running. Compensation could be applied to channel gain parameters if it becomes necessary to zero any position measurement offset.

COMMISSIONING

The stripline BPM system for the electron beam measurement was put into commissioning in Fall of 2017. Since then, there was once firmware updating in March of 2018 and one DSP module was replace due to the damaged AFE board.

One design feature was approved to be valuable especially at the beginning of the commissioning: the capability of the remote reset of the DSP modules which allowed quick recovery from the dead DAQ communication. Such situation disappeared after the firmware updating.

The BPMs installed on the common beam line had to see the much stronger proton beam which could damage the sensitive AFE that is designed for electron pulse. A customized designed high power BPF from Mini-Circuit had been installed in front of the DSP module for these BPMs.

One critical specification of the BPM system is the position measurement resolution which is specified as 10 μm rms. Due to the much larger beam centroid jitter at this stage of the AWAKE operation, the BPM's resolution performance is not obvious from the measurement data of each BPM. The Singular Value Decomposition (SVD) algorithm was applied to a recent run data from all 12 BPMs. Figure 6 shows the beam jitter for the vertical direction before and after the SVD, with the five most significant eigenmodes removed. In Fig. 6, the beam direction is indicated, and the horizontal axis is the event number, the vertical axis is the position in unit of mm. There is nearly no change for the beam jitter at the BPM430010, this could be explained by the fact that the acceleration cavity isolated this BPM from all other ones. Shown in both Fig. 6, and Fig. 7 that a strong correlated motion only exists at BPM430028 and 430039. At the BPM412345, a higher frequency beam jitter (or electronics noise) exists, which does not relate to any other BPM locations, this might be indicating a real electronics problem. Figure 8 shows the beam position S.T.D. values before and after the correlated beam centroid jitter is removed. These data indicated the best rms resolution reached to 6.2 μm at BPM#11.

CONCLUSION

For the first time in the world, on May 26 2018 AWAKE successfully accelerated electrons to 2 GeV from 19 MeV using a wakefield generated by protons through a 10 meter long plasma cell [4].

The performance of the stripline BPM system has been approved to be satisfied to assist the operation of the electron beamline and the precise alignment of the electron beam with the proton beam. Its input dynamic range extends beyond of the specified 100 pC to 1nC electron charge. One observed position rms resolution has reached to 6.2 μm from the recent run data, which is also within the specified rms resolution 10 μm.

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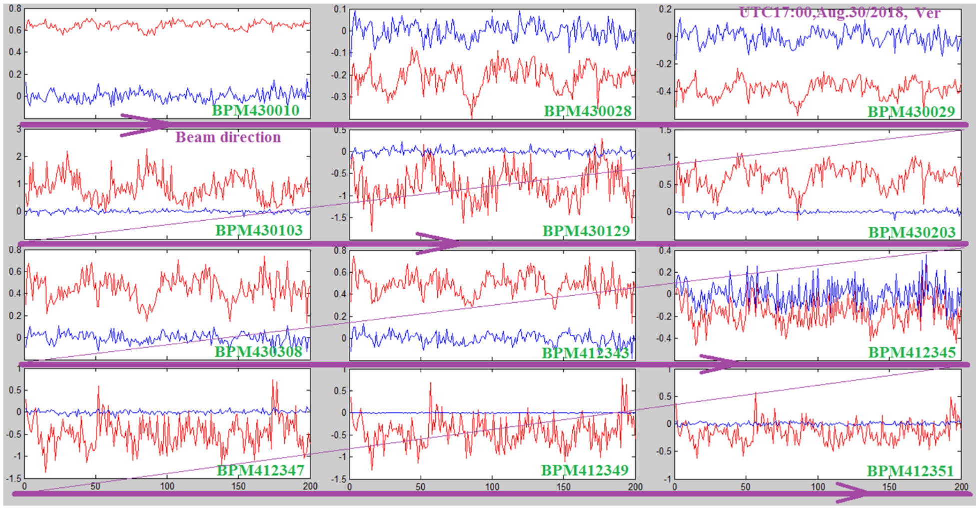

Figure 6: Correlated beam jitter vs. beam jitter removed through SVD algorithm.

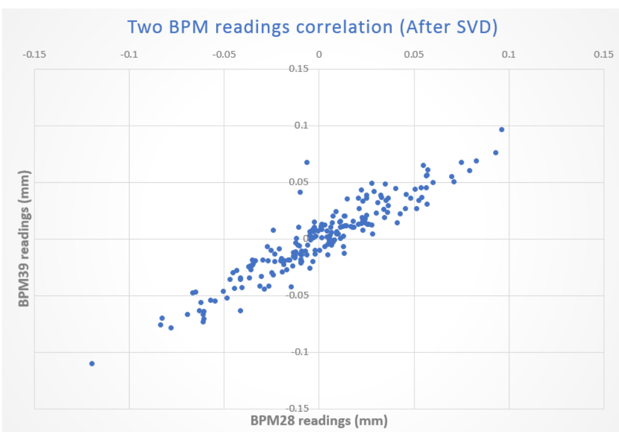

Figure 7: Correlated beam jitter at BPM430028,430039 after SVD.

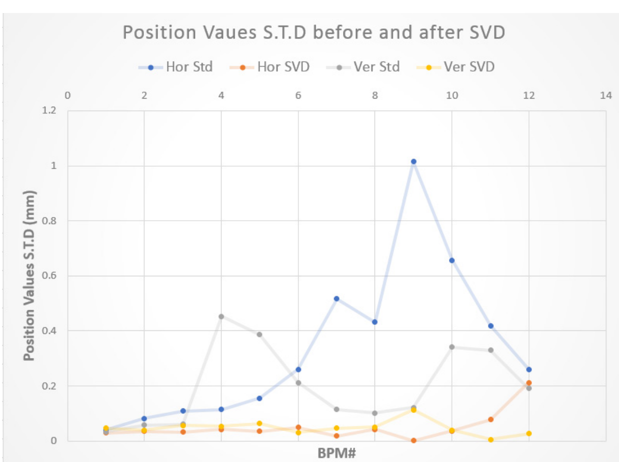

Figure 8: Beam position STD before and after SVD.

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