Physics 291: Senior Thesis Project

Beam Position Monitoring at Argonne Wakefield Accelerator

Spring Quarter Final Report

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I. Overview

The goal of our project is to develop a dependable beam position measurement system to study the transverse electron beam profile generated by the Argonne Wakefield Accelerator (AWA). Such system will enable us to better understand various properties of AWA electron beam and the accelerating capability of a wakefield structure. Currently we are testing the resolutions of two different types of position measurement methods: the Beam Position Monitoring (BPM) system adopted from Advanced Photon Source (APS), and direct imaging using Yttrium Aluminum Garnet (YAG) crystal.

Each method has its merit and shortcoming. BPM system is known for its few-micron sensitivity\(^1\), but it has never been applied at AWA, therefore we need to first calibrate the system and perform test measurements. On the other hand, although direct imaging with YAG produces convenient beam images and allow easy beam-position control, the uncertainty in position measurement is comparably large.

We also hope to develop a standard procedure for BPM usage at AWA.

II. Background on Wakefield Acceleration

In 1979, Tajima and Dawson’s paper “Laser Electron Accelerator” suggested that it is possible to produce relativistic plasma wave, propagating at nearly the speed of light, by using intense short-pulse laser beam\(^2\). This plasma wave can then be used to accelerate particles to high energy at a rate as high as 1GeV/cm. In the late 80’s, as laser
technology matured, experimental efforts to develop wakefield accelerators started. Argonne Wakefield Accelerator is among the few wakefield accelerators that studies this new acceleration method.

![Diagram of AWA beam pipe]

Fig. 1: A schematic diagram for the old AWA beam pipe.

AWA accelerates particles in the following way (Fig. 1). An electron beam is generated in the drive gun, and passes though the “wakefield device”, in our case it’s a ceramic tube, where the beam deposits some of its energy. Then a second beam, generated by the witness gun, is sent through the wakefield device to pick up the left-over energy, thus being accelerated.

II. BPM Measurement Circuit and BPM System Installation

The BPM system consists of three major electronic components (Fig. 2). First, four stripline pickup electrodes are attached to the beampipe, one in each transverse direction. When an electron beam bunch passes, its current excites the electrodes, sending a signal to the second BPM electronic component: the four resonant frequency cavities. These cavities are responsible for eliminating the portion of the signal in unwanted frequencies. We only want 2.856 GHz signal, because that’s the working frequency for the Logarithmic Amplifier (Log Amp), the third BPM component, which receives resonant cavities’ output signals and amplify them to give us DC signals observable on a scope.
In order to calculate beam position from final BPM signals, we need to use Log Amp input vs. output calibration (Log Amp calibration) and beam position vs. pickup electrode signal calibration (BPM calibration).

We assembled the BPM electronic parts and installed the system in the AWA beam line during fall of 2004 (Fig. 3).
III. Direct Imaging with YAG

Compared to the BPM system, how YAG acquires beam position measurement is more straightforward. A fluorescent, circular YAG plate with a diameter of 4cm is placed in the beam line, making a 45° angle with the direction of beam's movement (Fig. 4). As a beam bunch passes, the YAG screen lights up, while a camera captures the direct transverse beam profile and sends the image into a computer for analysis.

![Fig. 4: A YAG screen in the beam pipe.](image)

The AWA data acquisition program processes YAG image data for position measurement in the following way: for each beam image, the program plots beam intensity vs. horizontal/vertical direction, and fits Gaussian curves on both graphs. We take the peaks of these two fits as beam displacement from the centroid (Fig. 5).

![Fig. 5: A YAG beam image processed by the AWA data acquisition program.](image)
IV. Past Progress

1. *Benchtop measurements of individual BPM electronics:* in order for us to better understand BPM responses, we had a series of mini-measurements to study various properties of BPM system, especially resonant cavity behavior. With a network analyzer, we measured the quality factor Q of the cavity (Q ~ 870). A high quality factor implies the cavities can filter out unwanted signal efficiently. We also studied cavity input/output response, which helps us to estimate final BPM signals.

2. *BPM signal calculation:* we spent some time constructing a model to describe and predict BPM signals, in which the resonant cavity is assumed to behave like an RLC circuit, and an estimation of final BPM signal, given the charge of the beam bunch, is calculated.

3. *Log Amp Calibration* (Fig. 6): To calibrate Log Amp, we simply input a 2.856 GHz pulse and measure the DC output with a voltmeter.

![Log Amp Calibration CH. 1 & CH. 2](image)

Fig. 6: Log Amp calibration result for channel 1 and 2. Log Amp has four channels to amplify signals from the four transverse directions.

4. *BPM signal prediction verification:* In order to see if our calculation gives reasonable estimations, we excited the cavity with a pulse generator, varied the pulse-width, and sent the cavity output through Log Amp, and compare Log Amp output with predicted values. Comparing with the signals measured (Fig. 7), we see that we could predict how signals would change with different pulse-width, but our estimations are
not always accurate. However, the estimation is sufficient to give us an idea on the amount of signal we should expect.

Fig. 7: Verification of BPM calculation.

5. Preliminary BPM sensitivity test: To assure the BPM system is functional after the installation, we tested how well the BPM signals responded to beams placed in vastly different locations: top of the beam pipe, bottom, left, right and center. The beam position was controlled by magnets in the beam pipe and monitored via YAG direct image.

Fig. 8: The preliminary BPM sensitivity test shows that the system is functional and giving beam position measurements as seen on the YAG camera.
6. **Simultaneous BPM and YAG measurement**: Simultaneous measurement is the best way to compare YAG and BPM resolution. The AWA data acquisition system is automated to record BPM signals on the scope, while simultaneously saving YAG image files. We expect to see agreements between YAG and BPM position measurements, but the comparison charts shows there are considerable differences.

![x displacement chart](image)

**Fig. 9**: BPM and YAG measurement comparison, showing a clear disagreement. There are many possible reasons for this discrepancy, but one major factor is the lack of a set of dependable BPM calibration data.

7. **BPM re-calibration**: In the simultaneous BPM and YAG measurement, we used Advance Photon Source’s BPM calibration result\(^1\) to find BPM position measurement. But since the AWA particle beam has very different properties from APS beam, particularly we often have much larger beam displacement and beam cross-sectional area, it is possible that the APS calibration result is not suitable for our need. Here is the calibration measurement setup (Fig. 10): A section of a beam pipe is fixed on a movable platform, with four stripline pickups attached to the wall.

![BPM calibration setup](image)

**Fig. 10**: A part of the BPM calibration setup.
A thin wire is stretched through the middle of the beam pipe, one end is linked to a power supply and pulse generator to simulate particle beams. We can measure the displacement of the wire while recording BPM signals, giving the data needed for a calibration plot.

However, there are complications on how to process the data we collect. First there is the Log Amp question: should we include the Log Amp in the calibration or should we calibrate stripline pickups only? The APS seems to have included Log Amp in their calibration (Fig. 11), since the linear fits have negative slope.

![BPM calibration performed by APS. Notice the negative slopes and the narrow translation stage (-1 to 1 mm).](image)

But a calibration including Log Amp is not ideal in our case, since its linearity disappears quickly outside of 1mm-displacement range. The AWA beam can be displaced as much as 1~2cm, so a stripline-pickup-only calibration is preferred.

Another complication is how to read the data that's collected by an automated APS program. It records two kinds of signals: raw voltage and calibrated voltage. There is a confusion over which of these signals is the correct one to use.

V. Recent Progress – Direct BPM Measurement

Besides the discrepancy between YAG and BPM measurements and BPM calibration complications, there is another problem we faced at the beginning of spring quarter. We found a loose connection in one of the pickup electrodes (top channel), therefore, before we replace it, BPM cannot give accurate measurement on vertical position.
In attempt to solve these problems, we performed a direct BPM measurement.

**Setup:** We connect the Left (channel 2) and Right (channel 4) channels of the BPM stripline with two high quality resonant frequency cables, and measured pickup signals with a new 6GHz scope.

**Measurement:** Ideally we would like to have synchronized BPM and YAG measurements again so that we can compare their resolution at each shot. But since the fast scope was not setup on the AWA data acquisition program, we could not do the simultaneous measurement. Instead, we try to fix the beam at one position, and take separate measurements of BPM signal and YAG image. Five beam positions are tested: top, mid-top, center, mid-bottom and bottom (Fig. 12). They refer to beam position in camera image. At each beam position, we take 25 YAG images and around 12 BPM signals.

![Image of YAG images](image)

Fig. 12: YAG images for typical top, mid-top, center, mid-bottom, and bottom beam positions.

**BPM calibration verification:** We can compare YAG measurement to BPM measurements using different calibration methods: linear fit of the raw signal (Fig. 13), linear fit of the calibrated signal, and polynomial fit of the calibrated signal (Fig. 14).
BPM and YAG Measurement Comparison: After calculating beam positions for both methods, we plot the comparison charts below. The x-axis represent beam position, x=1 is top, x=2 is mid-top and so on. The error bar for each data point is the standard deviation of that measurement group.

From Fig. 15 we can see that the linear fit with raw signal gives the best BPM calibration. We will use this calibration for future measurement, unless other discrepancy arises.
Fig. 15: Comparison of different BPM calibrations with YAG measurement. We see the blue diamonds (raw calibration) are the closest to the red crosses (YAG measurements).

Fig. 16: Same comparison chart with only BPM position measurements calculated using raw signal calibration.

Although we have obtained a satisfying agreement between YAG and BPM measurements, from Fig. 16 we can see such agreement is lost at higher beam position.
(beam seen on the top of the YAG camera screen). There are some possible explanation, one is that we have collected some really weak BPM signals, and these signals are not as dependable due to the limited resolution of the scope. So we took out BPM signals under 50mV and plot the comparison chart again (Fig. 17), and indeed we see an improved agreement, but it is still not perfect.

![YAG/BPM measurement comparison excluding weak BPM signal (<50mV)](image)

**Fig. 17**: YAG and BPM measurement comparison excluding weak BPM signals.

Another possibility for their measurements to deviate is the cross-sectional area of the beam. When the beam was seen at the top of camera screen, it was typically less focused than other positions. It is possible that, for a widely dispersed beam profile, the direct imaging mechanism cannot capture the actual beam centroid.

Also, there is a small distance between the pickup electrodes and the YAG screen in the beam pipe. Our beam travels at an angle that depends on the deflection we give using the magnets, so it’s reasonable that, after passing the pickup electrodes, the beam is deflected even more before it hits the YAG screen. This will result in measurement discrepancies between YAG and BPM, particularly at large beam displacements.
VI. Future of Beam Position Monitoring at AWA

There are other measurements we should perform before we can start utilizing the BPM system at AWA.

1. *Simultaneous YAG and direct BPM measurement:* Our direct BPM measurement was fruitful, but not the most ideal setup. To best compare YAG and BPM resolution, we need to perform synchronized measurements. The 6 GHz scope has been successfully connected to the AWA data acquisition program, and we will be able to collect this data set as soon as the accelerator is ready to run.

2. *Pepper Pot Measurement:* The large cross-sectional beam size has been a complication in our study, and pepper pot measurement is an attempt to overcome this difficulty. This measurement consists of the addition of a thin tungsten plate with a small hole is inserted in the beam line, used to reduce beam size. A preliminary measurement showed that beam size was so overly reduced that we could not observe beam image on the YAG camera screen. We will need to make other adjustments.

3. *Simultaneous YAG/BPM measurement with all BPM components:* If a simultaneous YAG and direct BPM measurement is successful, then the next step would be testing the entire BPM system.

4. *Finalize a standard procedure for BPM usage:* If all measurements and testing are satisfactory, then we will be ready to put together a BPM manual. Most ideally we can write a program to automate BPM data acquisition and position measurement calculation.
VII. Conclusion

The goal of this project is to develop dependable beam position measurement system with sufficient resolution for AWA usage. AWA has been using YAG for a long time, and although it is straightforward and convenient, the uncertainty is comparably high. The BPM system, on the other hand, has much better sensitivity, but in order to adopt this new system, much work has to be done. One important task is finding the correct BPM calibration, and we have found a calibration model that works the best for the measurements we have done. There is still much work to be done before we can finalize a standard BPM usage procedure. But, once this is achieved, BPM will be a useful asset for AWA to study properties of wakefield accelerator, and maybe help to develop a more efficient accelerating mechanism.

3 Detail of the calculation is available at: http://home.uchicago.edu/~jhsin/AWA/BPM_calc.doc. The appendices are posted on project homepage: http://home.uchicago.edu/~jhsin/AWA.