

DESIGN OF THE STRIPLINE BPM FOR THE ADVANCED PHOTOINJECTOR EXPERIMENT*

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Abstract

We describe the design, bench testing, and initial commissioning of the shorted stripline beam position monitors used in the Advanced Photoinjector Experiment at Lawrence Berkeley National Laboratory. Our BPM's are characterized by extreme compactness, being designed to fit in the vacuum chamber of the quadrupole magnets, with only a short portion including the RF feedthroughs occupying additional beam pipe length. In this paper we illustrate the design process, which included extensive 3D computer simulations, the bench testing of prototype and final components, and the first measurements with beam. Their readout electronics is also described.

INTRODUCTION

The Advanced Photoinjector Experiment (APEX) is a test facility in operation at Lawrence Berkeley National Laboratory for the study and development of a high repetition rate, high brightness, electron injector for X-ray FEL applications [1]. The main beam parameters for the facility are described in Tab. 1.

Table 1: APEX Electron Beam Parameters

Parameter	Value	Units
Energy	750	keV
Bunch Charge	10^{-3} - 10^3	pC
Average Current	1 - 10^6	mA
Norm. Emittance (rms)	<1	μm
Bunch Repetition Rate	1 - 10^6	Hz
Bunch Length (rms)	1-60	ps

As part of the beam diagnostics [2] necessary for commissioning and the study of RF gun and different photocathode materials (Fig.1), we have designed, manufactured, tested and installed a series of stripline beam position monitors (BPM). The present position of the BPM's along the accelerator, together the other diagnostic devices, is illustrated in Fig.1.

These monitors had to satisfy the following requirements:

- Be compatible with existing 250 MHz digital readout electronics.
- Transfer impedance high enough to allow single bunch measurements at low charge.
- To be installed in the 1.5-inch diameter pipe, using as little space as possible.

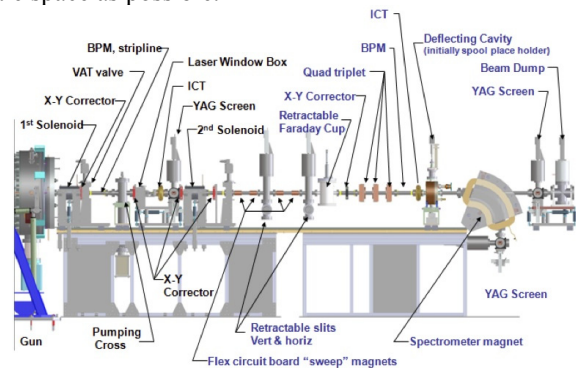


Figure 1: APEX diagnostics present layout.

In order to satisfy these requirements we developed a shorted stripline BPM, modifying a design used for the medium energy beam transport section of the Spallation Neutron Source at ORNL [3].

In the following sections we describe the design process, where the BPM physical parameters are analytically determined; the RF measurements on the assembled BPM's; the first measurements with beam, together with a summary description of the readout electronics and signal processing.

ANALYTICAL MODEL DESIGN

The analytical model for stripline BPM's is well established [4]. Assuming that one knows the minimum distance between opposed striplines (or *stay-clear*) h and wants to design a 50Ω matched system, the parameters to be chosen are the striplines width w , its separation from the vacuum chamber wall d , and its length L . These will determine the transfer impedance Z_{PU} , characteristic impedance Z_c and frequency response respectively.

We altered the SNS BPM design mentioned above, increasing h to 30 mm in order to satisfy the stay-clear. Lengthened the striplines to $L=140$ mm, to increase Z_{PU} at 250 MHz. w and d were kept the same, respectively at 6 and 1.5 mm, since we estimated the pickup response to be already sufficient. There are advantages in keep d small, since matching the feedthrough to the stripline becomes easier and we also wanted to keep as much distance between electrodes as possible, in order to widen the

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vacuum chamber between them, as it will be illustrated later. Although we would have liked to make the striplines even longer, so that the Z_{PU} maximum coincide with 250 MHz, that would have required a 300 mm long stripline and we chose 150 mm as the best compromise between space and transfer impedance constraints.

The choice of shorted striplines, rather than the classic termination on a dummy load, was made for two reasons: Saving four additional feedthroughs and 50 Ω loads per BPM and the possibility of installing the BPM inside large quadrupoles, thus saving space. Such quadrupoles would be present after the 30 MeV energy upgrade of the APEX project (Phase II).

The analytical expression of the transfer impedance for a shorted stripline is:

$$Z_{PU} = \left| \frac{V_P}{I_b} \right| = Z_c \frac{w}{\pi h} \left| \sin\left(\frac{\omega}{c} L\right) \right| \quad (1)$$

Where V_P is the voltage induced at the stripline feedthrough by a beam current I_b .

With our parameters, the peak value of Z_{PU} is 2.7 Ω at 536 MHz, while its value at 250 MHz is 1.8 Ω (see Fig.3).

Under the hypothesis of sufficiently short gaussian bunches, it is possible to estimate the peak value of the signal detected by processing the BPM frequency response around a center frequency f_0 much lower than the bunch spectrum rolloff frequency over a narrow bandwidth so that it is possible to consider Z_{PU} about constant without introducing a large error.

This is always verified for our beam parameters, so that we have:

$$V_{peak} \approx 2 \cdot BW \cdot Z_{PU}(f_0) \cdot q_{bunch} \quad (2)$$

It can be seen that for the ~20 MHz bandwidth we use, signal levels are of the order of about 70 $\mu\text{V}/\text{pC}$. Since we can operate with a few millivolts signals a 20 dB gain front end is sufficient for detecting even picocoulomb bunch charges.

The transverse position resolution δx for a centered bunch is related to the resolution of the pickup signal by

$$\delta x = \frac{r_p}{2\sqrt{2}} \frac{\delta V}{V} \quad (3)$$

For small charges a 100 μm resolution is satisfactory, which means being able to detect differences of about 2% in the detected signal between opposed striplines, which based on Eq.(2) can be estimated above 100 μV , to be compared to the ~4 μV thermal noise level.

For larger bunches of 100's of pC, a resolution of 10 μm is required by the slit emittance measuring system, which also requires similar resolution in measuring the stripline voltage.

COMPUTER SIMULATIONS AND TEST BENCH MEASUREMENTS

In order to validate our analytical estimates we performed extensive 3D computer simulations using CST's Microwave Studio electromagnetic analysis software [5]. We also measured the five BPM produced up to now in our microwave laboratory, using standard techniques such as the coaxial wire for beam coupling and transfer impedance and time domain reflectometry (TDR) for the characteristic impedance.

Computer Simulations

The CAD drawings of the BPM (Fig.2) where imported in Microwave Studio and we added a 1 mm diameter coaxial wire to simulate transfer and beam coupling impedance measurements.

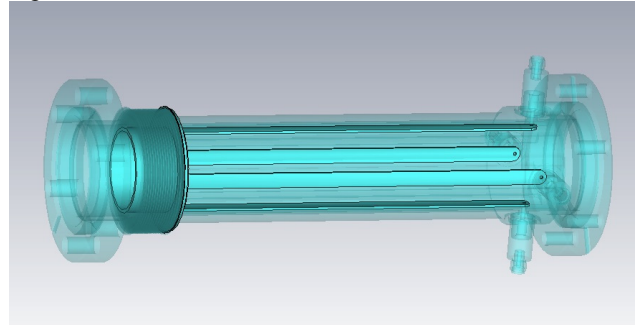


Figure 2: BPM CAD model.

The transfer impedance can be evaluated measuring the transmission S_{p1} between the upstream port and a feedthrough:

$$Z_{PU} = \sqrt{R_0 R_w} \frac{S_{p1}}{S_{21}} \quad (4)$$

where $R_0 = 50 \Omega$ is the reference impedance and $R_w = 204 \Omega$ is the coaxial line impedance. S_{21} is the transmission measured between the BPM pipe entrance and exit.

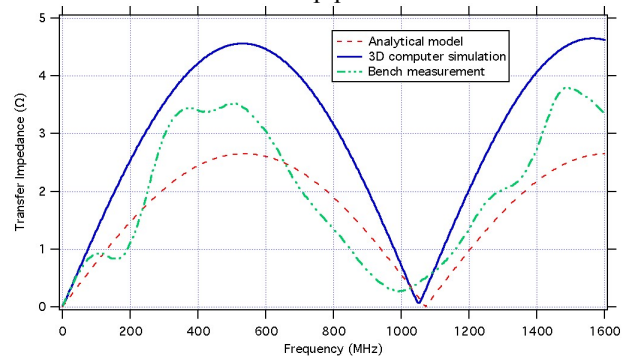


Figure 3: BPM transfer impedance derived from the analytical model (red, dashed), computer simulated (blue, solid), bench measured (green, dash-dot).

Results are shown in Fig.3. While the minimal frequency shift between the minima of analytical and computer simulated is negligible, there is a difference

between the two estimates almost exactly equal to $\sqrt{3}$ the origin of which is not clear at present.

With the same method we have also estimated the beam coupling impedance $Z_{||}$:

$$Z_{||} = -2R_w \ln(S_{21}) \quad (5)$$

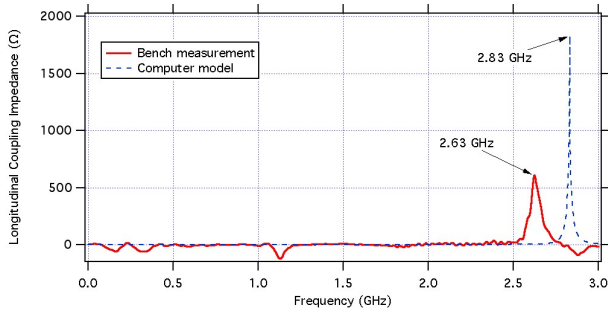


Figure 4: Beam coupling impedance computer simulated (blue, dashed), bench measured (red, solid).

We found an impedance peak around 2.83 GHz (Fig.4). Computer simulations of the field inside the BPM showed that this was due to a resonance in the bellows (Fig.5).

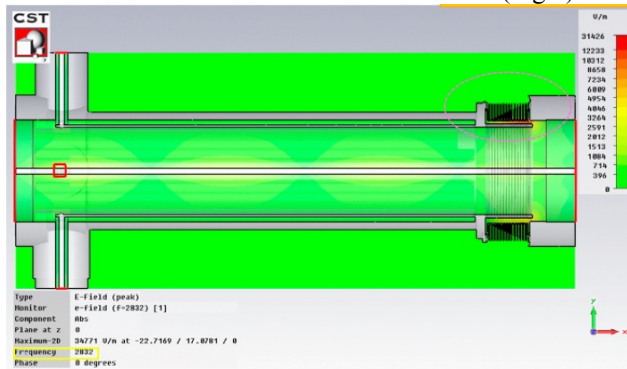


Figure 5: Bellows resonance simulated with Microwave Studio.

Although in principle this resonance could have been dangerous due to the possibility of heating the thin bellows, we estimated that the power absorbed from the beam is not substantial, after revising the peak impedance to a lower value, following the bench measurements shown in the next subsection.

Test Bench Measurements

All the five BPM produced insofar were at first measured using a HP 54750A digitizing oscilloscope with TDR capabilities. These measurements are used to verify the 50 Ω characteristic impedance of all the striplines and the feedthroughs quality. Figure 6 shows the result of such a measurement for the four electrodes of a BPM: The peaks between 60 and 70 Ω correspond to the feedthroughs, which are not of stellar quality, and the region between them and the drop (i.e. the short circuit) is a signal roundtrip on the striplines.

We also measured the BPM transfer and coupling impedances using the coaxial wire method, analogously to

what already done, in a virtual way, using computer simulations.

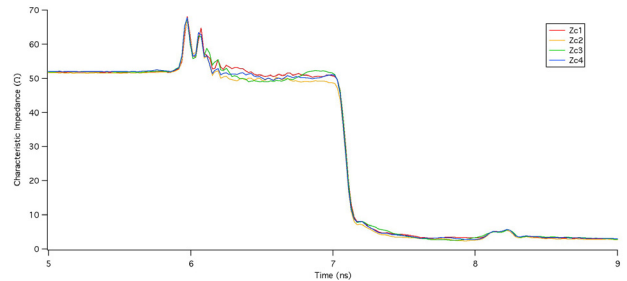


Figure 6: TDR measurement of a BPM characteristic impedance (all four striplines).

To this end we used a HP 8752C network analyzer and special cone transitions to match the 145 Ω characteristic impedance of the coaxial line, also measured using TDR, to the 50 Ω input impedance of our instrument. In this case we also had to measure a spool, or reference, piece, i.e. a section of beampipe with the same length and diameter of the BPM but without striplines, in order to normalize the response to the phase delay introduced by the length of the BPM and Eq.(5) becomes

$$Z_{||} = -2R_w \ln(S_{21} / S_{21}^{ref}) \quad (6)$$

The results are shown in Fig.3, where the bench measured impedance shows a good agreement with the analytical evaluation and in Fig.4, where the coupling impedance peak is shifted to 2.63 GHz and has a substantially lower value around 600 Ω. The small negative peaks in the impedance are obviously an artifact, which is caused by the absence of bellows on the reference and the consequent small differences in the length with the measured BPM.

BEAM MEASUREMENTS AND READOUT ELECTRONICS

As shown in Fig.1, several BPM's have been installed and tested with beam. Figure 7 shows the raw signal out of a BPM with 100 pC bunches, detected on a standard 500 MHz oscilloscope.

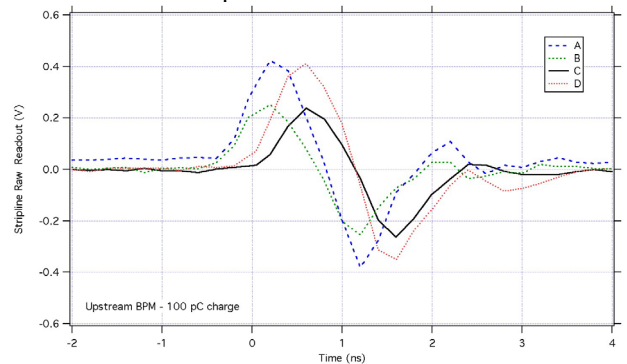


Figure 7: Raw signal on the BPM striplines from a single bunch passage (100 pC bunch charge).

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The picture shows a healthy signal, in the 100's mV range, which we can use to estimate the actual value of the transfer impedance from Eq.(2): Given that the bandwidth is large compared to the range over which Z_{PU} can be assumed constant, but the bunch spectrum is still rather flat at these low frequencies, we rather obtain a weighted average value for, which for $V_{peak} = 300$ mV is of the order of 3Ω . Not too far from measurements and estimates previously shown.

Readout Electronics

The readout is performed by direct digital subsampling, without using mixers, local oscillators, etc. The raw signal is band-pass filtered at 250 MHz, with a 20 MHz bandwidth, and the ring from each individual channel is continuously sampled at 100 MHz, so that no external triggering is required, but only a low-jitter ADC clock. In between bunches a calibration signal is used to control the variable gain amplification and balance the four channels.

The digitized signal is high-pass filtered at 4 kHz to remove any DC component and it is normally integrated as a sum of its squared values for 50 ms, after which a latch enable signal allows the accumulated sums from each channel to be sequentially stored in the control system, after the square root has been calculated.

It is possible, on request, to extract single bunch data at the 1 MHz maximum bunch repetition rate in APEX.

CONCLUSIONS

In this paper we have described our activities in the design and testing of the shorted stripline BPM's currently installed on APEX. We illustrated the philosophy behind our choice of the BPM parameters and how computer simulations and bench measurements were used to validate the analytical estimates and to test the assembled BPM before installation. The BPM's have proven themselves fully satisfactory during machine operations and their actual performance is not far from the initial estimates.

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