ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-WEPAL006

EXPERIMENTAL STUDY OF A DIFFERENTIAL BEAM INTENSITY MONITORING FOR THE CIADS LINAC*

Z. Xie†, J. Liang, Y. Ding, Hohai University, Nanjing, China
Z. Wang, Y. He, J. Wu, Y. Zhang, Institute of Modern Physics,
Chinese Academy of Sciences, Lanzhou, China

Abstract

A BPM based beam loss monitoring scheme for the China initiative accelerator driven subcritical (CIADS) facility has been proposed for the MEBT section of its high power Linac. In this scheme, a differential beam monitoring algorithm is utilized that relies on beam intensity measurements using BPM electrodes. Discussions of the experimental results for the scheme are presented. Further experiments have been performed with some promising results. This paper describes the experimental results with some analyses on measurement errors of the system. The proposed physical design of this system is described and further development is presented.

INTRODUCTION

A 25-MeV, 10-mA continuous-wave (CW) superconducting proton LINAC has been built as a prototype for the China initiative accelerator driven subcritical(CIADS) facility at the Chinese Academy of Sciences. The proton accelerator [9] employs a 1.5-GeV, 10-mA superconducting main Linac. The CW superconducting RF(SRF) cavities in the LINAC place many crucial requirements on the beam diagnostics for the CIADS facility. Various beam diagnostics tools are developed for the purpose of machine protection. In the superconducting Linac, errant beam occurs occasionally and it may deteriorate the beam pipe and damage the facility. It is desired to detect the errant beam in a timely manner such that the machine protection interlock can shut down the beam on detecting such an event.

Techniques to mitigate beam loss are developed at ADS to monitor beam loss and protecting the machine. For instance, ionization chambers and scintillation detectors are deployed at CIADS to detect radiations caused by beam loss. These detectors are sensitive to medium to high energy beam losses with a current resolution in the range of a few mA. A halo monitor ring was proposed at CIADS that utilizes a dedicated aperture to measure an intercepted current caused by beam halo scraping and transverse beam excursions. This instrument can achieve a current resolution in the range of a few nA and is mostly effective for chronicle medium energy beam loss. For lower energy beams in the Linacs, these techniques can be less effective because the beam may produce little radiation and the beam loss could be subtle in this condition.

Differential beam current monitoring (DBCM) [7] is a new direct technique to measure fractional beam loss. This method has been implemented at the Spallation Neutron Source (SNS) [2] and proposed in several laboratories [6, 8] as an alternative to the methods described above. Theoretically, differential beam monitoring can be applied to low energy beams since it relies on measuring the beam intensity that is proportional to the electric charges of the beam. In this method, difference signals of two or more beam intensity monitors are measured due to beam loss. DBCM systems can meet the requirements of machine protection systems of high power Linac. The DBCM system at SNS [2] is able to respond in less than 14 μs on a sudden beam loss.

The proposed DBCM systems will be operating in a similar manner for the FRIB's heavy ion superconducting Linac [8] and the ESS Linac [5]. Most DBCM schemes utilize ACCTs as the beam intensity monitoring electrode, but beam intensity [3, 10] can also be derived from the voltage signals measured with a BPM pickup electrode. This paper describes a possible scheme utilizing pickup electrodes for implementing the DBCM monitoring at CIADS. Experiments were carried out to study the feasibility ot this scheme. Limitations is also presented and followed by a discussion of the physical design of this system.

PRINCIPLES

Consider a stripline pickup electrode of radius b and a Gaussian beam bunch passing through its electrical center. Let σ stand for the rms beam bunch time length. We can measure the sum of voltages from four pickup electrodes. The spectrum of the measured signal at frequency ω is given by [11]:

$$\sum V(\omega) = Q \cdot Z_L(\omega) \cdot \frac{1}{(\omega b/\gamma\beta c)\, I_0} e^{-(\omega\sigma)^2/2}, \quad (1)$$

where Q is the charge of the beam, $Z_L(\omega)$ is the transfer function of the electrode, c is the speed of light, γ and β are relativistic factors, and I_0 is the modified Bessel function and it can be considered as a constant if the beam energy does not change at the pickup location. When the nominal bunch length is relatively small, Equation (1) can be rearranged and the total charge of the beam bunch is given as in the following equation:

$$Q = \frac{\sum V(\omega) \cdot (\omega b/\gamma\beta c)\, I_0}{Z_L(\omega)} \cdot e^{(\omega\sigma)^2/2}. \quad (2)$$

* Work supported by the National Natural Science Foundation of China (Grant No. 91026001) and the Fundamental Research Funds for the Chinese Central Universities
† zaipengxie@impcas.ac.cn

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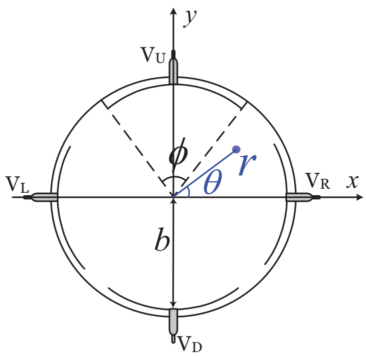

Figure 1: Schematic of the strip-line pickup electrode with a beam offset r.

Equation (2) shows that, for a centered beam, the beam intensity can be calculated from the measurement of the pickup electrode by calibrating the coefficients using a test beam. Therefore, methods to determine the coefficients is essential to implement the DBCM hardware using pickup electrodes.

When the beam is off the center by a distance r, the spectrum of the measured sum signal can be given [10] as:

$$\sum V_r(\omega) = V_L(\omega) + V_R(\omega) + V_U(\omega) + V_D(\omega)$$
$$= \sum V(\omega) \cdot \left(1 + \frac{1}{\phi} \sum_{n=1}^{\infty} \left[\frac{1}{n}\left(\frac{r}{b}\right)^{4n} \sin(2n\phi)\cos(4n\theta)\right]\right), \tag{3}$$

where ϕ and θ are the angles shown in Fig. 1 and the beam position is given in cylindrical coordinates (r, θ). Equation (3) shows that the beam intensity is not necessarily proportional to the measured sum signal from the electrodes with a off-center beam due to the second term at the right-hand side of the equal sign. The beam offset r can introduce measurement errors and it is worth finding out the requirements of beam condition for valid measurements.

EXPERIMENTAL RESULTS

To better understand the differential beam intensity measurement using pickup electrodes at CIADS, several experiments were carried out at BPM location 3, 4 and 5 of the CIADS Linac (the distance between BPM3 and BPM4 is about 36 7mm, and the distance between BPM4 and BPM5 is about 700 mm). For all the experiments, a 5 MeV pulsed beam was used. During the experiments, the beam loss was constantly monitored and can be considered at a minimal level. The sum of the measured amplitude from the four pickup electrodes is captured as the raw ADC counts from the BPM electronics and evaluated at the frequency of the beam pulse (162.5 MHz at CIADS). The experimental setup is described in Fig. 2.

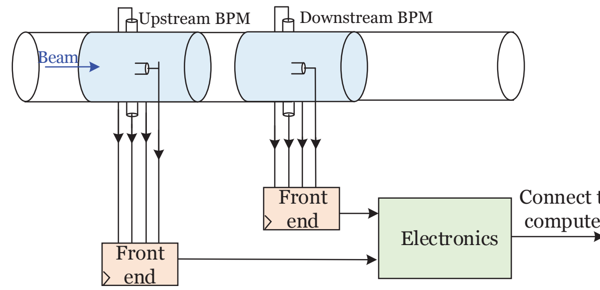

Figure 2: Experimental setup for the differential beam intensity measurement.

Centered Beam

The first experiment was performed on a centered beam with the beam intensity varying from 4 mA to 10 mA and each step was 0.5 mA. The sum of the amplitudes, $\sum V(\omega)$, versus the beam intensity is plotted in Fig. 3, where the buncher voltage was set to 95 kV and each data point was an average of 32 measurements. This figure shows that $\sum V(\omega)$ varies at different BPM pickup electrodes, but each measurement of $\sum V(\omega)$ grows linearly with respect to the beam intensity. Based on the measurements, a linear model can be used to fit the curve and this model will be used to calibrate each pickup electrode. Further measurements of $\sum V(\omega)$ can be converted to its corresponding beam intensity using this linear model. The steps were repeated by varying the buncher voltage[1] from 45 kV to 95 kV with a 10 kV increase for each step. Experimental results reveal that the measurement at each buncher voltage also presents a linear relationship between $\sum V(\omega)$ and the beam intensity.

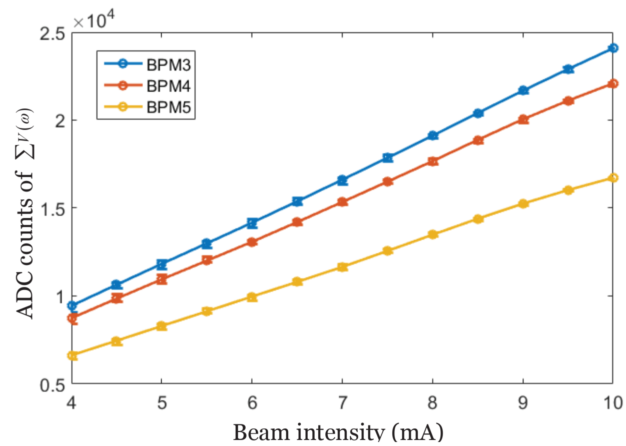

Figure 3: The sum of the amplitudes, $\sum V(\omega)$, versus the beam intensity.

The second experiment was to verify the model and estimate the errors of differential measurements by using this model. Figure 4 shows the average measurement error by using the model computed in the previous experiment where the absolute differential error E is computed as the following equation:

$$E = \frac{|G_a(\sum V(\omega)) - G_b(\sum V(\omega))|}{G_a(\sum V(\omega))} \tag{4}$$

[1] Bunch voltage is related to the buncher length and methods to measure bunch length at CIADS are still under development

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where G_a and G_b are the model function for each individual BPM electrode that can calculate the actual beam intensity by $\sum V(\omega)$. The blue curve in Fig. 4 is the measurement error between BPM3 and BPM4 and the red curve is between BPM4 and BPM5. In general, the average measurement error is less than 0.3%. However, the error between BPM3 and BPM4 is slightly better than that between BPM4 and BPM5.

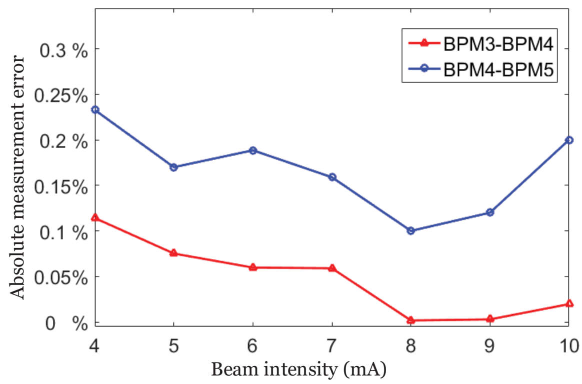

Figure 4: The average differential measurement error between BPM electrodes with a centered beam.

Off-Centered Beam

The third experiments were carried out when an beam is off the electrical center of the electrode by a distance r where $r \in$ [1 mm, 10 mm] (The radius of the beam pipe is about 25 mm at CIADS). The beam intensity was 5 mA and the buncher voltage was set to 95 kV. We follow similar steps as in the second experiments and the differential error E between BPM3 and BPM4 is shown in Fig. 5.

The experimental results reveal that the differential measurement error is less than 1% when the beam offset is less than 2 mm. But the measurement error becomes 1.3% when the beam offset is 5 mm and the error deteriorates rapidly when the beam offset increases.

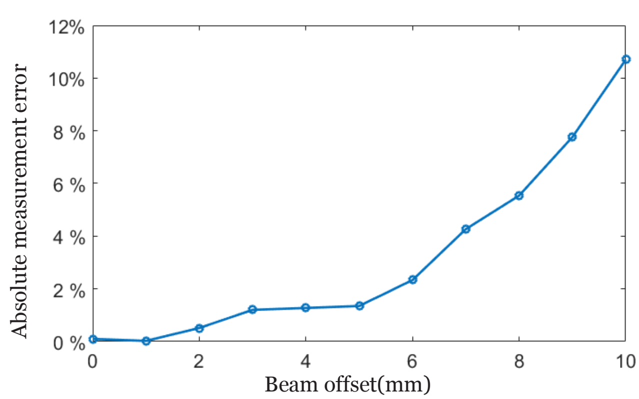

Figure 5: The average differential measurement error with an off-centered beam between BPM4 and BPM5 electrodes (the radius of the beam pipe is about 20 mm).

In order to correct the errors introduced by the beam offset, a 2D polynomial fit or a look-up table can be used. Further measurements should be made to establish the look-up table such that the nonlinear effect caused by the second term in Eq. 3 can be removed during production. The measurement requires varying both the angle θ and the beam offset r in finite steps while the beam intensity is set. This method introduces errors that can be reduced by using fine-grained steps. An alternative method [4] is to employ pickup electrodes with a larger radius. In addition, a circular split-plane electrode arrangement [12], or a single circular electrode can be employed in our application since they do not have non-linear effects. The beam offset, however, becomes less of an issue in the CIADS superconducting section because the beam offsets in those sections are typically less than 2 mm so as to mitigate potential damages to the SRF cavity.

SYSTEM IMPLEMENTATION

An FPGA-based hardware was proposed as an initial plan of the differential beam intensity monitoring system. The real-time signal processing needs to calculate the accumulated differential errors and present the data to the control system. The FPGA processing utilizes lookup tables to apply the models generated from the experiments. The signal processing on the FPGA also stores data samples in the local register and prepares for beam diagnostics upon errant beam events. At current stage, the proposed prototype is still under development. There are plans to integrate the FPGA card with the Libera [1] Single-Pass E BPM electronics in the near future.

CONCLUSION

Differential beam current monitoring is a novel technique to measure errant beam. In this paper, we examined practical requirements of utilizing pickup electrodes to implement the differential beam intensity monitoring scheme. Experimental results reveal that the proposed scheme can be effective by applying a linear model on the measured amplitude from the pickup electrodes; but the beam offset is an important factor that may limit the accuracy of the measurements. A discussion of the proposed physical design of this system is described and further development is presented.

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