

# A DIFFERENTIAL BEAM INTENSITY MONITORING FOR THE CIADS LINAC\*

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## Abstract

The high power Linac places many crucial requirements on the beam diagnostics for the China initiative accelerator driven subcritical (CIADS) facility. Measuring the beam loss is essential for the purpose of machine protections for the facility. A beam position pickup based differential beam current monitoring (BPDBCM) scheme has been proposed for the MEBT section at CIADS. Discussions of the principles for the scheme and the relationship between beam intensity measurement and the pulse length are presented. Simulations are performed and they demonstrate that the proposed system can be effective at the low energy section for the CIADS beam. This paper also describes the proposed implementation that is capable of detecting both the instantaneous and chronicle loss in real time.

## INTRODUCTION

The China initiative accelerator driven subcritical (CIADS) project is built [1] for developing clean nuclear power source by utilizing neutrons to transmute minor actinides and long-lived fission products (as nuclear waste) into shortlived or stable elements. Since its launch in 2011, the CIADS has been constructed at the Chinese Academy of Sciences where a high power linear proton accelerator is been built. The design of this proton accelerator [2] consists of an injector Linac and a 1.5 GeV, 10 mA superconducting main Linac. The high power Linac places many crucial requirements on the beam diagnostics for the CIADS facility. In the CIADS Linac, an errant beam may cause beam losses and damage the beam pipe. Hence, measuring the beam loss is essential for the purpose of machine protections for the CIADS facility. Methods to mitigate beam loss and provide a fast alarm at the event of errant beam are under development at the CIADS.

Beam loss is a universal problem in most high power Linacs around the world. Many techniques have been developed for measuring beam loss and protecting the machine. For example, beam loss monitoring (BLM) [3, 4] systems employ ionization chambers and scintillation detectors to detect radiations caused by beam loss. This technique, however, is mostly effective at a beam energy above 10–20 MeV with a loss current resolution in the range of a few hundred pA to a few mA. Halo Monitor Rings [5] utilize metal rings with a dedicated aperture to measure an intercepted current

caused by beam halo scraping and transverse beam excursions. This technique can measure a loss current of a few nA and is mostly effective to monitor chronicle beam loss at a beam energy around 10 MeV. 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) [6] is a new technique to measure fractional beam loss by monitoring the beam directly. This method can be applied to low energy beams since it does not require radiation detection. In this method, two beam current monitors are utilized to capture a beam loss in between by measuring changes in the beam intensity. A differential beam current monitoring system [7] has been successfully implemented at the Spallation Neutron Source (SNS) to measure beam loss in less than 14  $\mu$ s. The FRIB's heavy ion superconducting linac has also proposed a DBCM system [8] by integrating 12 ACCTs to provide a fast digital daisy chain of the machine protection status signal. A DBCM system [9] has also been planned for monitor large and sudden beam losses for the MEBT section of the ESS linac.

So far, the majority of the DBCM systems utilize beam current monitors (BCM) such as ACCT or DCCT when implementing the DBCM scheme. Beam position monitors (BPM) are capable of measuring beam current [10, 11] within certain conditions. In this paper, a beam position pickup based differential beam current monitoring (BPDBCM) scheme is proposed for the MEBT section at CIADS. Based on this scheme, we first simulated the beam current based on our facility conditions. Limitations of this scheme is also presented and followed by a discussion of the proposed physical design of this system.

## PRINCIPLES

A beam position pickup based differential beam current monitoring scheme can be adopted as an alternative to the DBCM scheme for several reasons. First, the proposed BPDBCM scheme only requires relative measurements that could bring better performance (i.e. in terms of response time, resolution, and noise) than using DCCTs for a low beam current. Second, BPMs do not suffer from droop in the beam current measurement compared with ACCTs. Third, the number of BPMs are more abundantly available at the CIADS linac facility compared with the ACCTs and DCCTs. Last but not the least, replacing a damaged ACCTs usually takes a significant amount of time in the order of months.

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To justify the proposed scheme, the first step is to understand information of the beam intensity from the measured signal [10] of the four BPM electrodes. In the case of CIADS, the BPM pickups are mostly button-type electrode as shown in Fig. 1. Assuming a Gaussian longitudinal bunch shape

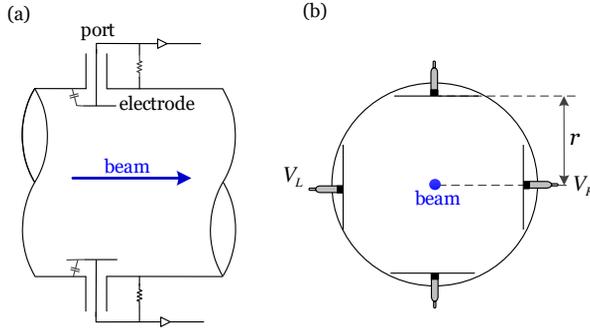


Figure 1: Schematic of the button-type pickup electrode with the beam pulse entering the electrode (a) The electrode structure along the beam traveling direction (b) The cross section of the electrode structure perpendicular to the beam traveling direction.

with a rms bunch time length of  $\sigma$ , the amplitude of the beam current harmonic  $J(\omega)$  at the frequency  $\omega$  is given by

$$J(\omega) = Q \cdot e^{-(\omega\sigma)^2/2} \quad (1)$$

where  $Q$  is the total charge of the beam bunch. When the beam offset  $r$  in the beam pipe of radius  $b$  is relatively small, the sum of the signals [12] from the four BPM electrodes is given by

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

where  $Z_L(\omega)$  is the transfer function of the electrode related to its geometry,  $r$  is the radius of the pickup aperture,  $c$  is the speed of light,  $\gamma$  and  $\beta$  are relativistic factors, and  $I_0$  is the modified Bessel function.

In the case of CIADS linac MEBT, since the nominal bunch length is relatively small (around  $2.6\text{mm}$ ) and the beam energy does not change at the BPM location, the Bessel function in Eq. (2) can be considered as a constant during calculation. Rearranging Eq. (2), we can derive the total charge of the beam bunch as in the following equation:

$$Q = \frac{\sum V(\omega) \cdot (\omega r / \gamma \beta c) I_0}{Z_L(\omega)} \cdot e^{(\omega\sigma)^2/2} \quad (3)$$

Based on Eq. (3), we may calculate the number of particles and hence determine the change of beam intensity from the measured beam signal of the BPM electrode where the coefficients in Eq. (3) can be calibrated using a test beam.

## SYSTEM SIMULATION

Measuring beam intensity using BPM outputs, however, depends on the beam position and can produce a nonlinear calibration [13] when the beam is off the electrical center of the electrode. To better understand the measurement from the BPM electrodes. We simulated the beam position based intensity measurement with a relatively low beam energy using the CST Particle Studio [14]. Assume that the measurement and the beam offset  $\Delta x$  has a dependency as is given by

$$\frac{V_L - V_R}{\sum V} = k(\Delta x) \cdot \Delta x \quad (4)$$

where  $k(\Delta x)$  is a function of  $\Delta x$ . In the simulations, we set the beam pipe radius as  $20\text{mm}$ . The beam energy is set as  $5\text{MeV}$  ( $\beta = 0.1029$ ) and the beam current is  $10\text{mA}$  as the nominal beam at CIADS which requires a particle bunch with approximately  $Q = 6.15385 \times 10^{-11}\text{C}$ . We assume the beam bunch has a Gaussian longitudinal bunch shape with a rms bunch length of  $\sigma = 4\text{mm}$ . The beam is first centered at the electrical center of the BPM electrode. Then a small amount of offset is applied to the beam center as shown in the following equation (due to the symmetric property of the electrode, negative offsets are omitted here):

$$\Delta x = \{0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10\text{mm}\} \quad (5)$$

In the first simulation, we measure  $k(\Delta x)$  and plot the percentage of difference  $(k(\Delta x) - k(0)) / k(0)$  with respect to  $\Delta x$  as shown in Fig. 2.

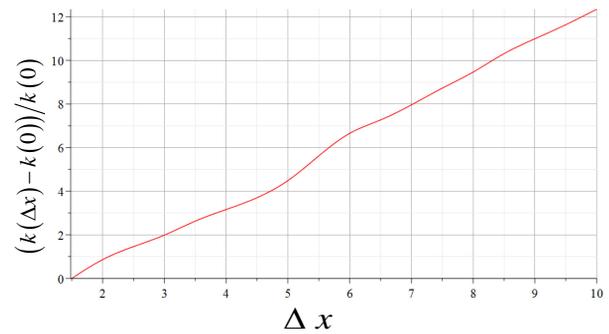


Figure 2: The percentage of difference  $(k(\Delta x) - k(0)) / k(0)$  with respect to  $\Delta x$ .

Figure 2 shows that the measurement error in  $k(\Delta x)$  grows linearly with respect to  $\Delta x$ , which suggests that BPMs should be chosen carefully as the beam intensity measuring tool. For a requirement of less than 5% in measurement error at CIADS, the beam offset has to be less than  $5\text{mm}$ . Hence, for an accurate beam intensity measurement, we must consider calibrating this nonlinear effect by incorporating the beam position information.

In the second simulation, the beam bunch length is set as  $4\text{mm}$ ,  $6\text{mm}$ ,  $8\text{mm}$  and  $10\text{mm}$ ; while  $\Delta x$  varies between  $\pm 5\text{mm}$ . We measure the sum of the BPM electrode signal with respect to the beam bunch length and the simulation results are shown in Fig. 3. The result shows that the mea-

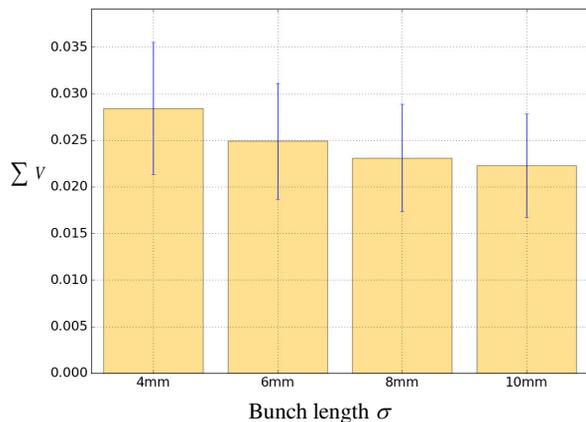


Figure 3: The sum of the BPM electrode signal with respect to the beam bunch length  $\sigma$ .

sured sum of the BPM electrode signal depends on the beam bunch length; and it decreases while the bunch length increases, given that the number of particles does not change. Therefore, a proper calibration is required when designing the signal processing algorithm for our proposed BPDBCM scheme for a particular beam bunch length.

## SYSTEM IMPLEMENTATION

The machine protection at CIADS requires less than  $10\mu\text{s}$  response time for the BPDBCM system. In the initial plan for the system, the time-critical features are implemented in the FPGA and the monitoring is performed in real time. The Real-Time signal processing needs to calculate statistics and present the data to the control system. Figure 4 shows a diagram of the proposed system setup.

The measured signals from the four BPM electrodes are sent to a high-Z pickoff and then summed together. The summed signal is passed through bandpass filter, linear amplifier, and sent to a splitter. One output of the port from the splitter is sent to the raw data display; and the other output is feeding a directional coupler and then divided in to two branches, where a high dynamic range current measuring scheme similar to Ref [15] is implemented such that the system can combine the signals from two signal channels with different resolutions to achieve a relatively high dynamic range. The signals are finally feeding to the ADC on the FPGA board and to produce the alarm signal.

The FPGA processing utilizes lookup tables to calibrate out the known parameters according to Eq. 3. The signal processing on the FPGA also includes an equalizer to correct for dispersions of the electronics and to compensate for cable length mismatch. Each data sample will be stored in the local register and prepare for (1) the beam intensity difference between consecutive pulses  $\Delta I_c(t)$ . (2) beam intensity difference between the current and previous current pulse for

both the upstream ( $\Delta I_L(t)$ ) and downstream measurement ( $\Delta I_D(t)$ ).

In order to provide a capability of measuring the chronic beam loss, a time windows is applied by summing the difference signals during this predefined time window. The results from the summed signal ( $\Delta I_c(t)$ ,  $\Delta I_L(t)$  and  $\Delta I_D(t)$ ) will be compared to a predefined threshold. Further beam studies are required to understand the predefined time window and the threshold for the CIADS linac to produce the alarm signal.

At current stage, the proposed system is still under development. Our initial plan is to employ a NI FlexRIO [16] with 2 GB of memory on board. Further plans include utilizing the BPM module of Libera Single-Pass E [17] to integrate the functionality with our BPM electronics.

## CONCLUSION

Differential beam current monitoring is a new technique to measure fractional beam loss by monitoring the beam current. BPM is an alternative instrument for measuring beam current. In this paper, we examined the issues in adopting BPMs to implement the differential beam current monitoring. We examined the relationship between the beam intensity and the measured BPM signals. A beam position pickup based differential beam current monitoring (BPDBCM) scheme is proposed for the MEBT section at CIADS and limitations of this scheme is also presented. Simulations results show that the proposed scheme can be effective at the low energy section for the CIADS beam; but the beam offset and bunch length are two important factors that may limit the accuracy of the measurements.

A discussion of the proposed physical design of this system is also presented. The proposed system will be implemented on the FPGA and the monitoring is performed in real time. The proposed BPDBCM system is expected to protect the MEBT from beam losses and abort the beam in less than  $10\mu\text{s}$  when beam loss happens over a predefined threshold.

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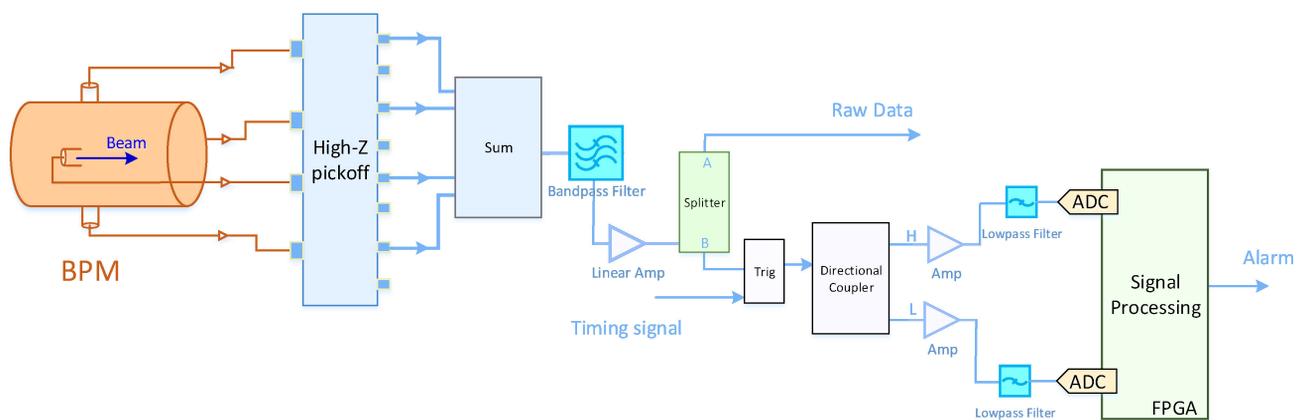


Figure 4: Diagram of the the BPBCM System.

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