



**BNL-98608-2012-CP**

***Beam position monitor for energy recovery linac***

**I. Pinayev**

*Presented at the International Beam Instrumentation Conference 2012 (IBIC 2012)*  
Tsukuba, Japan  
October 1-4, 2012

**Collider-Accelerator Department**

**Brookhaven National Laboratory**

**U.S. Department of Energy  
DOE Office of Science**

Notice: This manuscript has been authored by employees of Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. Department of Energy. The publisher by accepting the manuscript for publication acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes.

This preprint is intended for publication in a journal or proceedings. Since changes may be made before publication, it may not be cited or reproduced without the author's permission.

## **DISCLAIMER**

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or any third party's use or the results of such use of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof or its contractors or subcontractors. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

# BEAM POSITION MONITOR FOR ENERGY RECOVERY LINAC\*

I. Pinayev<sup>#</sup>, BNL, Upton, NY 11973, USA

## Abstract

The energy recovery linacs have co-propagating beams inside the same vacuum vessel. These beams can have different trajectories, which should be distinguished by beam position monitors (BPM). In this paper we present a concept of a BPM utilizing the phase information for calculation individual position of each of the two beams (accelerating and decelerating). The practical realizations are presented and achievable accuracy is estimated.

## INTRODUCTION

Most commonly used method for BPM is based on the evaluation of the signals induced on the pick-up electrodes (PUEs) by a circulating beam. Beam position is calculated from the signal amplitudes using delta over sum [1]. For the vertical plane BPM with two PUEs the equation is

$$y = k \frac{U_{up} - U_{down}}{U_{up} + U_{down}} \quad (1)$$

where  $U_{up}$  and  $U_{down}$  are the amplitudes,  $k$  is a scaling factor, which is determined by geometry. For a symmetrical system and beam in the center both signals have equal amplitudes and the corresponding position readback is zero.

With two (or more) beams circulating inside the vacuum chamber we need to separate the signals and process them individually. For the colliders with beams moving in the opposite directions this task is solved by utilizing the striplines, which have directional properties. The signals appear on the different ports and conventional processing units can be utilized.

This technique is not suitable for energy recovery linacs (ERL) where two or more beams co-propagate through a vacuum system and each beam has its own trajectory.

## PROPOSED METHOD

For ERL with two co-propagating beams the time delay between accelerated and decelerated bunches is fixed by design and it becomes possible to employ the phase of the PUE signal to extract information on the position of each bunch. If bunches, separated by a flyby time  $\Delta t_{12}$ , have different positions then each PUE sees different longitudinal “center of gravity” (see Fig. 1) and there is a phase shift between two signals. For a processing unit, utilizing signal processing at frequency  $\omega$ , and small displacements of the first and the second bunches  $\delta_1$  and  $\delta_2$  ( $S\delta_1, S\delta_2 \ll 1$ , where  $S=1/k$  is a sensitivity coefficient) we can write the linearized equations:

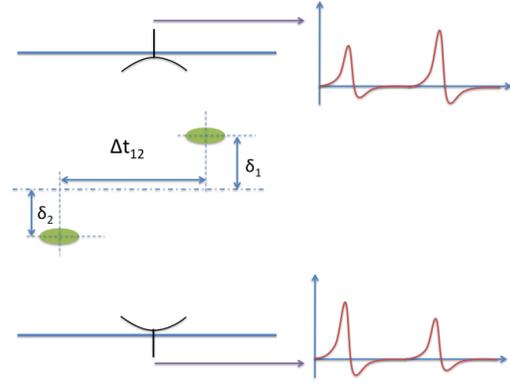


Figure 1: Signals induced on the pick-up electrodes by two bunches with different coordinates. Because of bunches' displacements the amplitudes of the induced voltages differ.

$$\begin{aligned} U_{up} &= U_1(1 + S\delta_1) \sin \omega(t + \Delta t_{12}/2) + \\ &\quad U_2(1 + S\delta_2) \sin \omega(t - \Delta t_{12}/2) \\ U_{down} &= U_1(1 - S\delta_1) \sin \omega(t + \Delta t_{12}/2) + \\ &\quad U_2(1 - S\delta_2) \sin \omega(t - \Delta t_{12}/2) \end{aligned} \quad (2)$$

When both bunches have equal charges (a valid assumption for ERL) then we re-write Eq. 2 as

$$\begin{aligned} U_{up} &= U_0 \cos \frac{\omega \Delta t_{12}}{2} (2 + S(\delta_1 + \delta_2)) \sin \omega t + \\ &\quad U_0 S \sin \frac{\omega \Delta t_{12}}{2} (\delta_1 - \delta_2) \cos \omega t \\ U_{down} &= U_0 \cos \frac{\omega \Delta t_{12}}{2} (2 - S(\delta_1 + \delta_2)) \sin \omega t - \\ &\quad U_0 S \sin \frac{\omega \Delta t_{12}}{2} (\delta_1 - \delta_2) \cos \omega t \end{aligned} \quad (3)$$

Neglecting second order terms we can estimate amplitudes ( $A = \sqrt{U_{sin}^2 + U_{cos}^2}$ ) of the signals induced on PUE

$$\begin{aligned} A_{up} &\approx 2U_0 \left(1 + S \frac{\delta_1 + \delta_2}{2}\right) \cos \frac{\omega \Delta t_{12}}{2} \\ A_{down} &\approx 2U_0 \left(1 - S \frac{\delta_1 + \delta_2}{2}\right) \cos \frac{\omega \Delta t_{12}}{2} \end{aligned} \quad (4)$$

Substitution of the found amplitudes into the Eq. 1 gives

$$\hat{y} = k \frac{S(\delta_1 + \delta_2)}{2} = \frac{(\delta_1 + \delta_2)}{2} \quad (5)$$

That means that using information on the amplitude we measuring the average position of the beam. Now we will consider the phases of the signals. Using the same assumptions we will find

\*Work supported by Brookhaven Science Associates under Contract No. DE-AC02-98CH10886 with the U.S. DoE  
#pinayev@bnl.gov

$$\begin{aligned}\varphi &\approx \frac{U_{\cos}}{U_{\sin}} \\ \varphi_{up} &\approx \frac{S(\delta_1 - \delta_2)}{2} \tan \frac{\omega \Delta t_{12}}{2} \\ \varphi_{down} &\approx -\frac{S(\delta_1 - \delta_2)}{2} \tan \frac{\omega \Delta t_{12}}{2}\end{aligned}\quad (6)$$

and difference of the two phases gives us the difference between two positions

$$\delta_1 - \delta_2 = k \frac{\varphi_{up} - \varphi_{down}}{\tan(\omega \Delta t_{12}/2)} \quad (7)$$

The processing frequency is usually equal to the RF frequency. Such a choice allows processing of any fill pattern because all bunches are separated by a multiple of the RF period. In the ERL distance between bunches can be different. It may be as small as half of the RF wavelength because the decelerated bunch should be in the opposite phase vs. accelerated one. Moreover, this distance can differ from the multiple of the half periods due to the shifts in the merge lines. Also, there is no revolution period in the ERL but only a round-trip time. Hence, choice of the processing frequency is somewhat arbitrary and can be used for optimization of the system. There are frequencies that should be avoided: if  $\cos(\omega \Delta t_{12}) = 0$  then there is no signal for the average position calculation and with  $\sin(\omega \Delta t_{12}) = 0$  phases will be constant and difference in orbits can not be found. Therefore, the processing frequency should be in between close to  $\omega = \frac{\pi}{\Delta t_{12}} \left( \frac{1}{4} + N \right)$ , where  $N$  is an integer.

## ACCURACY

Modern digital beam position electronics have the required capability to process both amplitude and phase of the PUE signals [2].

To estimate the accuracy of the measurement let us consider vector diagram shown in Fig. 2. When the measurement error is not correlated with the signal the probable error will draw a circle around the end of the vector and r.m.s. phase error will be equal to the signal to noise ratio of the amplitude measurement

$$\sigma_\varphi = \sigma_A / A \quad (8)$$

That means that achievable error in the difference of position is the same as for the average position. For the system described in [2] r.m.s. position error is 3 microns for  $k=10$  mm, which means that noise is  $3 \times 10^{-4}$  of the signal level and the ratio is close to the r.m.s. fluctuations of the phase measurements  $0.01^\circ$  ( $1.75 \times 10^{-4}$  radians).

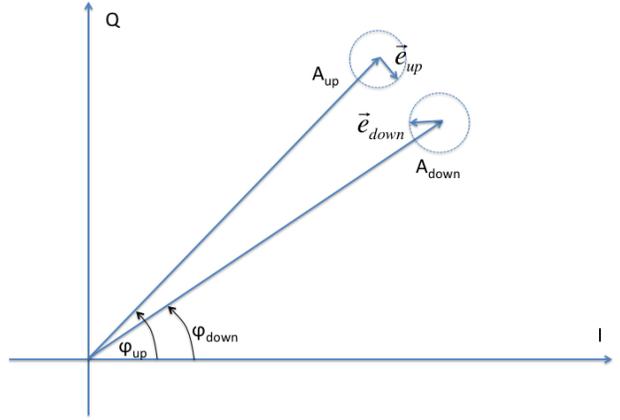


Fig. 2. Vector diagram for the PUE signals. Two longer vectors indicate phases and amplitudes of the signal when two smaller ones show the noise amplitude.

So far we have neglected phase shifts in the system associated with propagation of the signals the cables and in the processing electronics. The system transfer function will not be identical for all channels and a phase shift corresponding to the identical beam positions should be established. Otherwise these phase shifts will include a systematic error in the measurement of the difference of the two positions. Similarly, the unequal gain and/or losses in the channels generate systematic offset in the average position readback.

Both phase and amplitudes can be calibrated using a RF generator with a splitter. In this case the whole chain from the cable to electronics can be characterized. For the phase calibration exclusively it is also possible to use exclusively the accelerated bunches (dumping the beam at high energy). In this case the BPM processing unit sees signal from a single bunch, and there are no ambiguities associated with the second bunch.

## FOUR PUES SYSTEM

In the system with four pick-up electrodes, as shown in Fig. 3, the beam position is calculated with the modified equations

$$\begin{aligned}\bar{x} &= k_x \frac{U_B - U_A + U_C - U_D}{U_A + U_B + U_C + U_D} \\ \bar{y} &= k_y \frac{U_B - U_C + U_A - U_D}{U_A + U_B + U_C + U_D}\end{aligned}\quad (9)$$

As before, for the small beam displacements we can write

$$\begin{aligned}
U_A &= U_0(1 - S_x\delta_{x1} + S_y\delta_{y1}) \sin \omega(t + \Delta t_{12}/2) + \\
&\quad U_0(1 - S_x\delta_{x2} + S_y\delta_{y2}) \sin \omega(t - \Delta t_{12}/2) \\
U_B &= U_0(1 + S_x\delta_{x1} + S_y\delta_{y1}) \sin \omega(t + \Delta t_{12}/2) + \\
&\quad U_0(1 + S_x\delta_{x2} + S_y\delta_{y2}) \sin \omega(t - \Delta t_{12}/2) \\
U_C &= U_0(1 + S_x\delta_{x1} - S_y\delta_{y1}) \sin \omega(t + \Delta t_{12}/2) + \\
&\quad U_0(1 + S_x\delta_{x2} - S_y\delta_{y2}) \sin \omega(t - \Delta t_{12}/2) \\
U_D &= U_0(1 - S_x\delta_{x1} - S_y\delta_{y1}) \sin \omega(t + \Delta t_{12}/2) + \\
&\quad U_0(1 - S_x\delta_{x2} - S_y\delta_{y2}) \sin \omega(t - \Delta t_{12}/2)
\end{aligned} \tag{10}$$

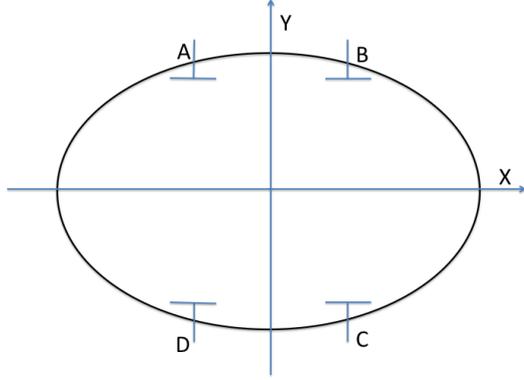


Fig. 3. Geometry of the four PUE beam position monitor. Such configuration is used to avoid exposure of the PUEs to the synchrotron light.

With the similar to the above calculations we can find that Eq. 9 is applicable for the calculation of the average beam position when the difference can be found from

$$\begin{aligned}
x_{diff} &= \frac{k_x}{\tan(\omega\Delta t_{12}/2)} [(\varphi_B + \varphi_C) - (\varphi_A + \varphi_D)] \\
y_{diff} &= \frac{k_x}{\tan(\omega\Delta t_{12}/2)} [(\varphi_A + \varphi_B) - (\varphi_C + \varphi_D)]
\end{aligned} \tag{11}$$

### SUPPRESSION OF THE CABLE DRIFTS

The temperature changes and other slow processes can change physical length of the cable or phase velocity of the signal in the cable. To suppress the drifts one can lower the processing frequency to the range where the sensitivity to the variations of delays is less. Unfortunately, it also lowers the sensitivity to the position difference due to the  $\tan(\omega\Delta t_{12}/2)$  term. To have both high sensitivity to the differential beam position (and low noise) and to suppress influence of drifts we can convert down the PUE signals. In this case the sensitivity is defined by sum of the local oscillator frequency and processing frequency, while drifts are defined by processing frequency only. Local oscillator signal should be brought to the PUE with a single cable and split to required number of mixers with shortest connection.

### REFERENCES

- [1] R.E. Shafer. "Beam Position Monitoring", BIW'89, AIP Conf. Proc. 212 (NY, 1990), p. 26.

- [2] M. Znidarcic et al., "Testing of New Hadron Beam Phase and Position Monitor at CIEMAT Laboratory," DIPAC'11, Hamburg, May 2011, MOPD26, p. 104; <http://www.JACoW.org>