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I. Pinayev

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Collider Accelerator Department

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Proposed Test of the Two Beam BPM at RHIC*

I. Pinayev
Collider-Accelerator Department, BNL, Upton, NY11973, U.S.A.

Abstract

The essence of the ERL operation implies that at least two beams (accelerated and decelerated) are co-propagating in the same vacuum vessel and each beam has its own trajectory. The existing beam position monitors measure only "average" trajectory but not that of an individual beam, unless the time separation between bunches is so large that one can resolve individual bunches.

It was proposed to use phase information of the pick-up signal to extract information on the orbit "difference". We are planning to conduct experiments at RHIC to test the proposed idea. The approach and experiment set-up are described in the paper.

INTRODUCTION

Energy recovery linacs (ERL) are considered as next step in development of accelerators with record parameters such as luminosity for the colliders and brightness for the synchrotron radiation light sources. Design for electron-ion collider (EIC) at Brookhaven National Laboratory (BNL) considers implementation of the ERLs for hadron cooling [1].

The essence of the ERL operation implies that at least two beams (accelerated and decelerated) are co-propagating in the same vacuum vessel and each beam has its own trajectory with more beams co-propagating in the common accelerator section. The conventional beam position monitors (BPM) will measure only "average" trajectory but not that of an individual beam, unless the time separation between bunches is so large that one can resolve individual bunches [2].

With increase of the average current and, hence, the bunch repetition rate it becomes not possible. For example, in the EIC the separation between accelerating and decelerating bunches can be as short as 1 nanosecond making it impossible to utilize the gate switches. Using frequency domain processing [3] is questionable due to deconstructing interference of accelerated and decelerated bunches which have 180 degrees phase shift in the RF frequency. To overcome the problem, we propose to utilize phase information of the signal induced on the pick-up electrodes by the circulating beams [4, 5]. Preliminary calculations show that in case of the difference in the position of two beams the phase difference is directly proportional to their relative displacement.

The approach can be used also to monitor the position of the beams in the colliders.

PROPOSED PRINCIPLE

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 method. For the vertical plane BPM with two PUEs the equation is

$$y = k\,\frac{U_{up}-U_{down}}{U_{up}+U_{down}} \tag{1}$$

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 from two beams appear on the different ports and conventional processing units can be utilized. The stripline technique is not suitable for energy recovery linacs where two or more beams propagate through a vacuum system in the same direction.

We propose the following technique. If bunches are separated by a flyby time Δt_{12} and have different positions, then each pick-up electrode 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 ω, and small displacements of the first and the second bunches δ_1 and δ_2 ($S\delta_1$, $S\delta_2 \ll 1$, where $S=1/k$ is a sensitivity coefficient) we can write the linearized equations:

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

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

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

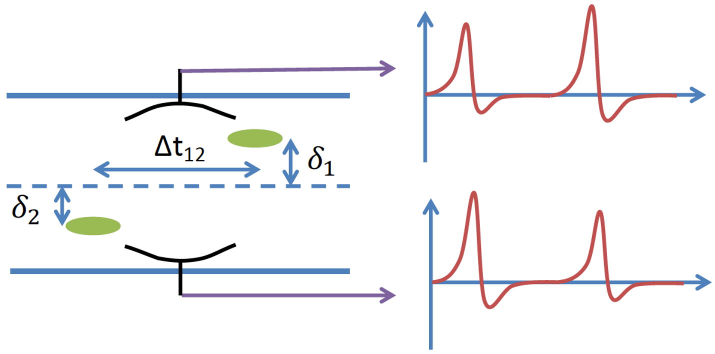

Figure 1: Signals induced on the pick-up electrodes by two bunches with different coordinates. Because of different bunch displacements the amplitudes of the induced voltages differ.

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

$$A_{up} \approx U_0\big(2 + S(\delta_1 + \delta_2)\big)\cos\frac{\omega\Delta t_{12}}{2}$$
$$A_{down} \approx U_0\big(2 - S(\delta_1 + \delta_2)\big)\cos\frac{\omega\Delta t_{12}}{2} \quad (4)$$

As it was said before, the information on the amplitude corresponds to the average position of the beams. Now we will consider the phases of the signals. Using the same assumptions, we will find

$$\varphi_{up} \approx \frac{S(\delta_1 - \delta_2)}{2}\tan\frac{\omega\Delta t_{12}}{2}$$
$$\varphi_{down} \approx -\frac{S(\delta_1 - \delta_2)}{2}\tan\frac{\omega\Delta t_{12}}{2} \quad (4)$$

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

$$\delta_1 - \delta_2 = k\frac{\varphi_{up} - \varphi_{down}}{\tan(\omega\Delta t_{12}/2)} \quad (5)$$

Figure 2 shows how filtered to single frequency signals will look for various beam positions.

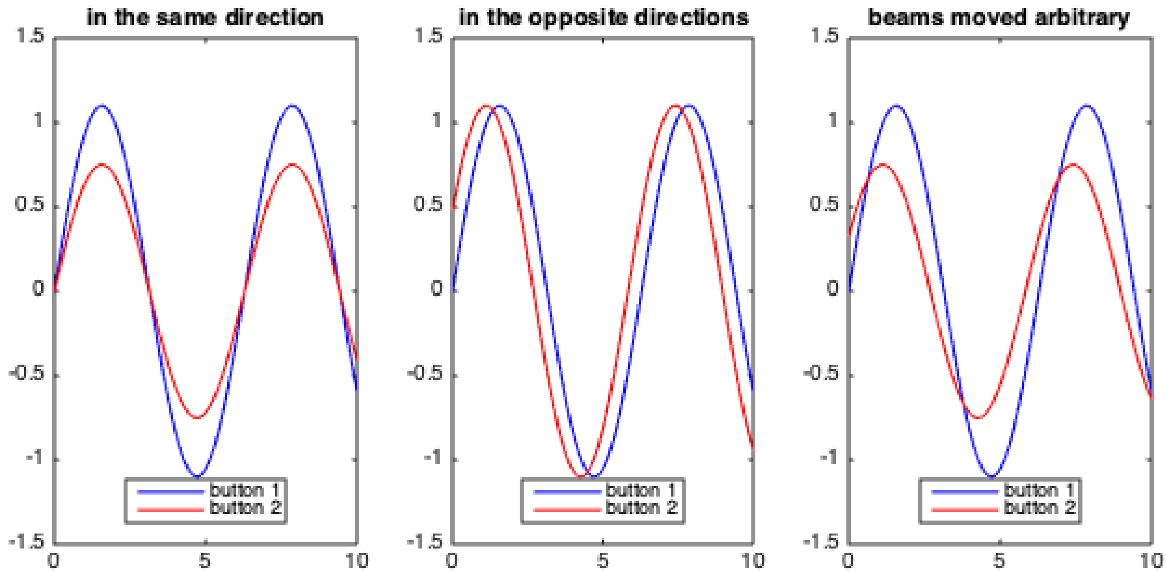

Figure 2: Traces of the filtered PUE signal for various beam displacements. With both beams on the axis of the beampipe both signals will have the same amplitude and phase. When both beams are moved in the same direction by equal amount then the amplitudes will differ but phase will be the same. When beams are moved in opposite directions by the same amount the amplitudes will be equal but the will be a phase shift. For arbitrary displacement both amplitude and phase will be different.

Modern beam position monitors utilize the direct digitization of the induced signals and digital processing. Phase information is readily available but in most cases is discarded. However, in the proposed system the processing frequencies should not be the RF frequency as in most conventional BPMs. This is due to the fact that accelerated and decelerated bunches are shifted by 180 degrees in phase. We need not only to study feasibility of the device but also to develop an algorithm for choosing the processing frequency.

EXPERIMENTAL SET-UP

We will use hadron RHIC beams in the common section to test the receivers with actual beam. RHIC has two beams propagating in the same vacuum vessel on the interaction regions (Fig. 3). We will use hardware of the coherent-electron cooling experiment installed in the IR2 [6] as well as RHIC beam instrumentation. Since for a collider time delay between two beams is not half of the RF frequency, the initial processing frequency will be the first harmonic of beam repetition frequency (9.3 MHz) and will explore other frequencies as well.

There are presently seven PUE which are equipped with diplexers to separate signals for the hadron and electron BPMs. The lumped LC diplexer ZDPLX-2150-S+ by Mini-Circuits has lower passband from DC to 25 MHz and higher passband above 30 MHz. At low frequency port the insertion loss is below 1 dB at 18.6 MHz (the second harmonic of beam repetition rate). There are also two DX BPMs located on the same straight that are part of RHIC Instrumentation. We will acquire RHIC type V301 BPM processors [7], which firmware will be modified to suite out needs. The set of pass-band filters will be used for selecting the processing of frequency. Narrow band filters (SBP-21.4+) or similar will be used to prevent folding in components from the other Nyquist zones. The signal will be digitized and processed with FPGA for further reduction of the bandwidth and improving signal-to-noise ratio. Either long buffer can be saved or digital filtering can be used. The BPMs for CeC tuned for 9.3 MHz frequency can be also used but this will set limits on the filling pattern.

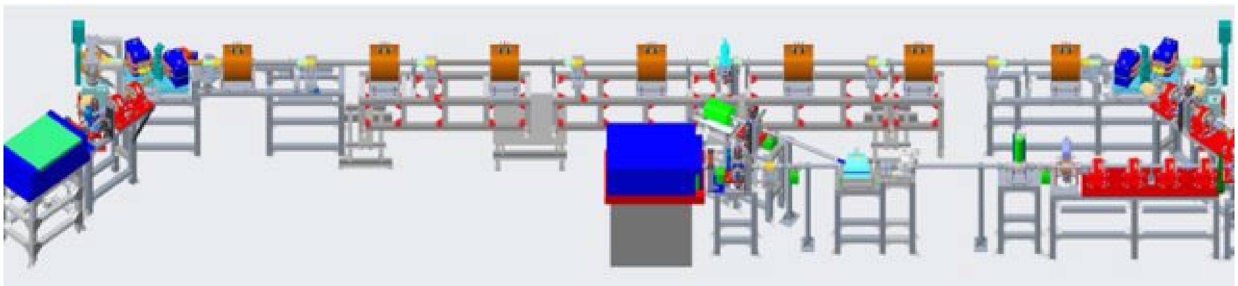

Figure 3: Layout of the straight section in the interaction region IR2.

There are four BPM pick-ups available in the coherent electron cooling section and we can control and measure beam position in the arcs independently as well as adjust bunch separation in time by changing the RF settings in the RHIC. Two quadrupoles located at the same straight section can be also used to measure the beam trajectories independently with possibility to extrapolate beam trajectories to the location of the BPMs.

Since RHIC is a collider the beams are counterpropagating and the arrival time difference varies from BPM to BPM, it gives us additional tool to investigate the BPM operational principle. RHIC revolution frequency is 78 kHz and there are 120 buckets meaning that frequency of the bunches is 9.3 MHz we will first test the second harmonic of 18.6 MHz. RF system can be used to adjust separation in time of two rings bunches. There is also flexibility in the filling pattern.

The RHIC control system provide information for the individual bunch intensity, which will be used for study of mismatch in the intensity of two beams. This is important since ERL can have beam losses.

TEST PROGRAM

The measurements will start with establishing phase shifts in the individual channels. It will be performed with single ring filled (test both rings fill) the long-term stability can be studied during regular RHIC operations when during refill only one ring has circulating beam. We will study spectral contend of the PUE signal to evaluate best frequency for signal processing.

For each ring filled we will establish the dependence of the beam trajectory in the common section with BPM readings just outside the common section to find independent way to steer the beams in controlled manner.

The first test will be aimed at proof-of-the-principle. With beams with equal intensity and known trajectories will calculate the positions using Equations 1 and 5 with time separation measured with oscilloscope connected to the BPM button (part of the CeC diagnostics) and known distances between the elements. Next, we will steer the beam and measure change in the orbit. The BPM readings will be compared with measurements based on the steering by the quadrupoles.

We will change the timing between bunches using RHIC RF and study the system applicability for obtaining reasonable readings including small separation time.

We will study systematic errors due to the unequal beam intensities when intentionally reduce circulating current in one of the rings using scrapers.

The described above measurements will be performed with different processing frequency (will replace bandpass filters for new ones) and/or filling pattern in RHIC.

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