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PROPOSED BPM-BASED BUNCH CRABBING ANGLE MONITOR*

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Abstract

A tilted (i.e. with different transverse displacements of the bunch head and tail) bunch traversing a button beam profile monitor will produce signals on opposite pickup electrodes that will have different degrees of distortion depending on the tilt angle. In particular, the zero-crossing time difference between the two signals will be approximately proportional to the tilt angle. We perform simulations to study this effect as a possible diagnostic tool for measuring the crabbing angles in a future electron-ion collider.

INTRODUCTION

The collisions in the proposed electron ion collider at eRHIC [1] at the Brookhaven National Laboratory (BNL), rather than being head-on, will occur at a crossing angle of 22 mrad. The reasons for this design choice [2] include the need to minimize beam-beam effects and to reduce synchrotron radiation interference at the detectors. To compensate for the geometric luminosity loss such a crossing angle would cause, both the ion and the electron bunches will be transversely tilted ("crabbed") [3] by so-called crabbing cavities located upstream of the interaction point (IP) so the colliding bunches completely overlap, i.e. collide "head on" at the IP. After the IP, the bunches are "de-crabbed" by a second set of cavities.

Various beam diagnostic devices will be required to achieve and maintain the required performance of these cavities. These devices will include very high frequency "head-tail" monitors [4] and streak-camera-based instruments for the short electron bunches [5]. For the ions, practical locations for such devices will be far from the IP where the experiment is located. One of the other five RHIC IP locations could be used, or any point with the appropriate phase advance with respect to the cavities. Devices located at such locations will be used to optimize individual cavity performance by adjusting phase and amplitude and by verifying that excessive higher-order-mode (HOM) amplitudes are not present. However, when both the "crabbing" and "de-crabbing" cavities are on, as is required during operation, these devices can only be used to verify that adequate crabbing cancellation has been achieved.

We propose here to install a 4-button beam position monitor (BPM) with small buttons as close as possible to the experiment for continuous monitoring of the ion bunch crabbing angle during operation. As described in the following sections, we take advantage of the relatively long ion bunches and we calculate and simulate the crabbing-angle-dependent bunch-shape differences between signals from opposite BPM pick-up electrodes (PUEs). The ion bunch length used for these examples was 80 mm RMS while more recent eRHIC preliminary designs use somewhat shorter bunches (~50 mm RMS).

EXCEL SPREADSHEET SIMULATIONS

The simulation effort is simplified by assuming that in the cylindrical BPM only the TEM mode is excited by the relativistic bunch and that the instantaneous charge induced on each PUE is proportional to the linear charge density of the bunch segment located in front of the PUE and is a function of that segment's position as given in reference [6]. A linear BPM calibration would have been adequate too, except for the cases where we study the effects of missteered bunches. The TEM mode assumption mentioned above is strictly valid only for bunches that are parallel to the axis. But Particle Studio (PS) [7] simulations, shown later, indicate that this approximation is valid in the present case since the crabbing angle is small (11 mrad).

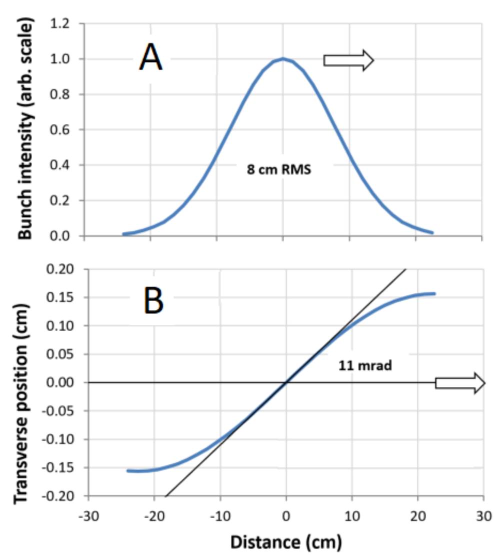

Figure 1: Bunch intensity (A) and transverse position (B) of an 8 cm RMS bunch crabbed at an angle of 11 mrad by a 336 MHz cavity.

The instantaneous bunch intensity used in the simulations as function of longitudinal position is shown in Fig. 1A and the transverse position of the crabbed bunch is shown in Fig. 1B. Due to the crabbing, the head of the bunch is closer to one PUE than to the opposite one, and vice versa regarding the tail of the bunch. Therefore, the signals induced on these opposite PUEs are not identical as shown in Fig. 2A. The signal shown in Fig. 2 B results from taking the difference of these two signals and dividing the result by the sum of their peak values. It is this normalized difference signal that will be used to measure the crabbing

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angle. Before discussing this further, we verify this simple approach with PS simulations.

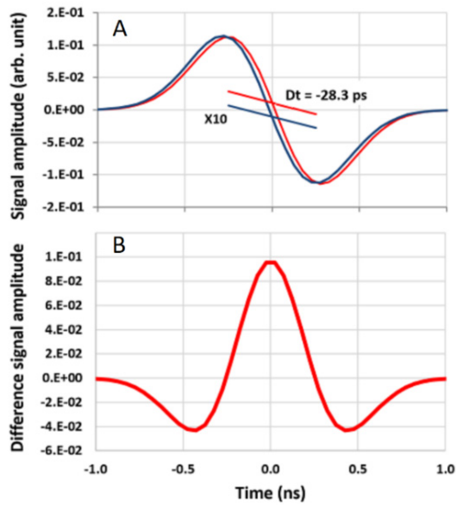

Figure 2: A) Signals induced on two opposite BPM PUEs by the bunch described in Fig. 1. B) Difference of the signals shown in A) normalized to the average of the peak values.

PARTICLE STUDIO SIMULATIONS

A 60 mm diameter cylindrical BPM model was used for the simulations. The "button" PUE diameter is 10 mm which is small enough compared to the 80 mm RMS bunch width to be well approximated by point-like PUE's used in the previous section. Since Particle Studio has no provision for specifying a crabbed bunch, we simulated such a bunch with the superposition of 27 shorter bunches distributed in time and intensity as shown in Fig. 3 and shifted laterally following the pattern shown in Fig. 1B. Also shown in Fig. 3 is the sum of these bunch intensities approximating well an 80 mm RMS Gaussian bunch with a total charge of 12.5nC.

The simulated signals that result are shown in Fig. 4 for the two opposite PUEs. We now compare the zero-crossing time difference with the same value obtained in the simple simulation described in the previous section and we see the values are 28. 5 and 28.3 ps respectively which is as good an agreement as could be expected. It is this zero-crossing time difference which multiplied by the signal slope determines the amplitude of the difference signal. That simulated difference signal is shown in Fig. 5 and is similar to the Excel simulation result shown in Fig. 2B. Here we show the unnormalized signal to give an indication of the actual signal strength that can be expected in a realistic case.

Good agreement between the two models was also found when studying sensitivity to beam offsets. We will therefore use the simple Excel model described in Section 1 to show a calibration curve and the sensitivity to beam offsets and other errors.

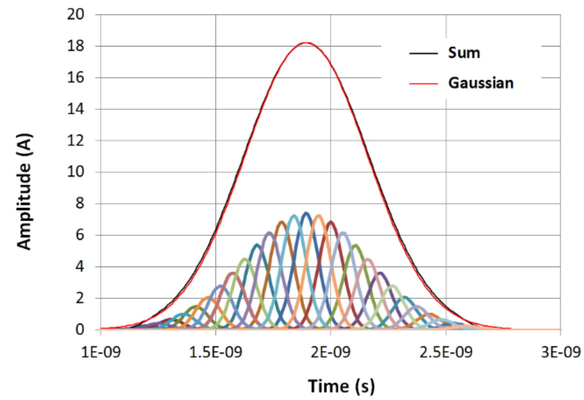

Figure 3: 27 bunches used as input to simulate the 8 cm RMS crabbed bunch. The individual bunches have a 1.6 cm RMS width, they are displaced laterally according to the pattern shown in Fig. 1B and their sum approximates a 8 cm RMS, 12.5 nC Gaussian crabbed bunch.

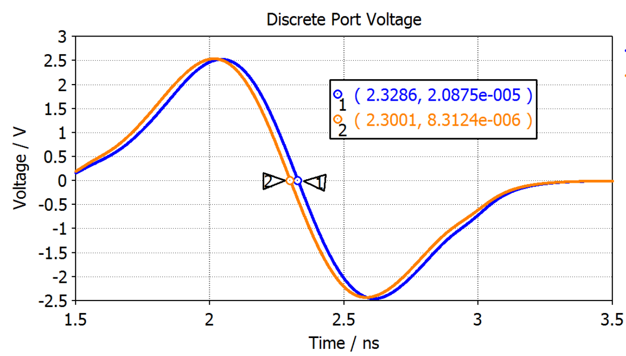

Figure 4: Particle Studio output for the two, opposite, horizontal PUEs when using a 60 mm diameter BPM with 10 mm diameter PUEs with a simulated crabbed bunch input described in Fig. 3.

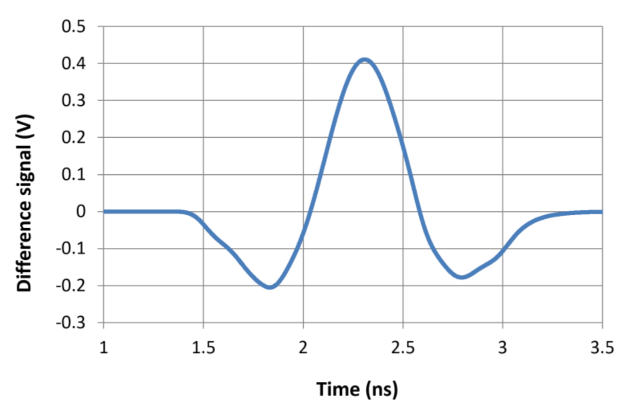

Figure 5: Difference signal obtained by using the simulation output shown in Fig. 4.

CALIBRATION AND ERROR-SOURCES

The normalized signal ratios used for monitoring the crabbing angles are (A0 - B0)/(Amax + Bmax) where A and B are the signal amplitudes at the waveform maximum and around the zero-crossing point. These ratios as function of the crabbing angles are shown in Fig. 6 for three

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different BPM radii. Fig. 8 shows these ratios as function of bunch length for a fixed 11 mrad crabbing angle

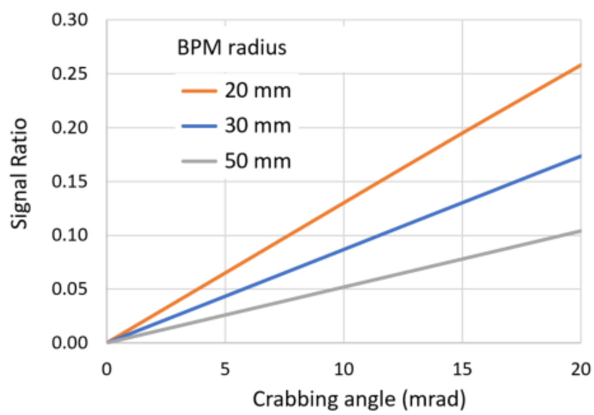

Figure 6: Signal ratios (A0 - B0)/(Amax + Bmax) as function of crabbing angles for three BPM radii.

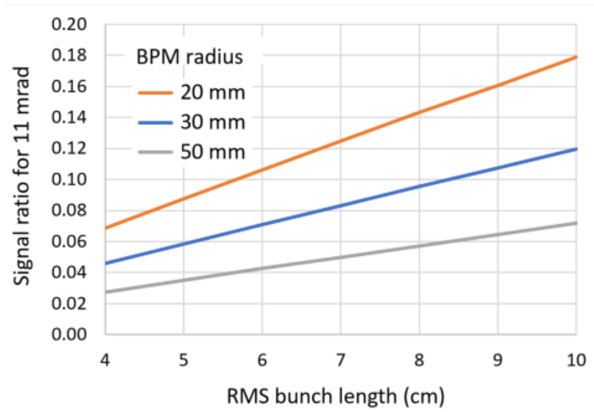

Figure 7: Signal ratio as function of RMS bunch length for three BPM radii.

Errors caused by beam offsets and by cable length deviations are shown in Figs 8 and 9 respectively

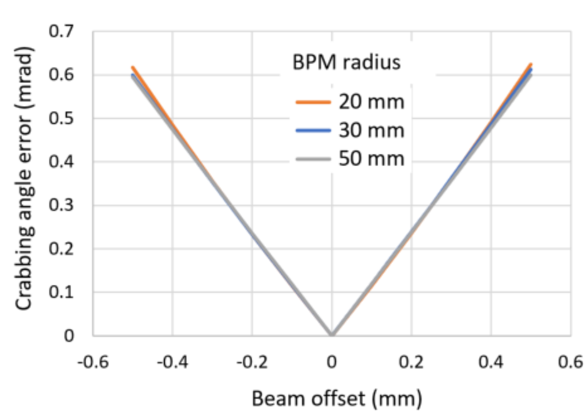

Figure 8: Signal ratios (A0 - B0)/(Amax + Bmax) as function of beam offset for three BPM radii.

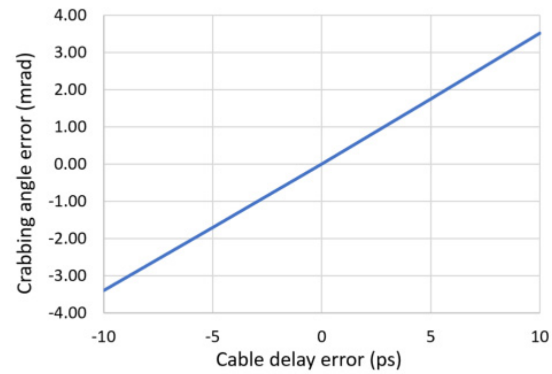

Figure 9: Crabbing angle errors as function of cable delay variations.

DISCUSSION AND CONCLUSIONS

We see from Fig. 7 that the sensitivity of the measurements is a strong function of the BPM radius which should therefore be made as small as possible. The sensitivity to bunch length shown in Fig. 7 will need to be addressed by either relying on measurements from other instruments or by deriving the bunch length from the difference in time between the minima shown in Figs 2B and 5.

Finally, the extreme sensitivity to small delay variations shown in Fig. 9 needs to be addressed. A constant delay error is equivalent to a zero-offset for the measurement and can be determined by turning off the crabbing cavity or by reversing its phase. However, variations due to temperature fluctuations over long cable runs are very difficult to mitigate and should be avoided. Therefore, the difference signal will be obtained locally using short cables. This can in principle be achieved with local digitizers. Due the high radiation environment, a fast differential pulse transformer will probably be used instead. A good candidate is a specific very fast differential signal splitter [8] used in reverse as a signal combiner. The rise-time of this device is 21 ps and should therefore have minimal impact on the measurement sensitivity.

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[7] CST Particle Studio, https://www.cst.com/products/cstps

[8] Differential Pulse Splitter model PSPL315, Tektronix, Inc.