PROPOSED PULSE STRETCHING OF BPM SIGNALS FOR THE POSITION DETERMINATION OF VERY SHORT AND CLOSELY SPACED BUNCHES*

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Abstract

A proposal for a future ultra-relativistic polarized electron-proton collider (eRHIC) is based in part on the transport of multiple electron beams of different energies through two FFAG beam transports around the 3834 m long RHIC tunnel circumference in order to recirculate them through an Energy Recovery Linac (ERL) for their stepwise acceleration and deceleration. For each of these transports, the beams will travel in a common vacuum chamber horizontally separated from each other by a few mm. Determining the position of the individual bunches is challenging due to their very short length (~12 ps rms) and their temporal proximity (less than 4 ns in some cases). Providing pulses adequate for accurate sampling is further complicated by the less-than-ideal response of long coaxial cables. Here we propose two approaches to produce enhanced, i.e. stretched, pulse shapes of limited duration; one based on specially shaped BPM electrodes and the other one on analog integration of more conventional stripline BPM signals. In both cases, signals can be generated which contain relatively flat portions which should be easier to sample with good precision without requiring picoseconds timing accuracy.

INTRODUCTION

A plan is being developed for replacing the Relativistic Heavy Ion Collider (RHIC) by a high energy electron proton collider (eRHIC) [1]. The proton beam would be accelerated and stored in one of the existing RHIC rings while the 16 GeV or 21 GeV electrons would be accelerated and decelerated in multiple passes through an Energy Recovery Linac (ERL) [1, 2]. The present design calls for two electron beam transport arcs, located in the RHIC tunnel, both based on a Fixed-Field Alternating Gradient (FFAG) lattice design [1]. There would thus be several electron trajectories within each of these two FFAG arcs, slightly displaced horizontally and nominally at the same vertical height. Figure 1 shows an example of a short portion of such trajectories through a set of three FAG magnets in the "high energy" FFAG beam transport.

Accurately monitoring the positions of these beams at multiple locations around the arcs is a major challenge because some of these very short bunches (~12 ps rms) are separated in time by less than 4 ns, and because no beam position monitor (BPM) pick up electrodes (PUEs) may overlap the orbit plane due to the intense synchrotron radiation. Various alternative options are being considered to mitigate these difficulties, such as providing so called pilot bunches, well separated in time from the regular bunch sequence and also the possible use of synchrotron radiation generated in or near the visual range to measure orbit positions with optical systems.

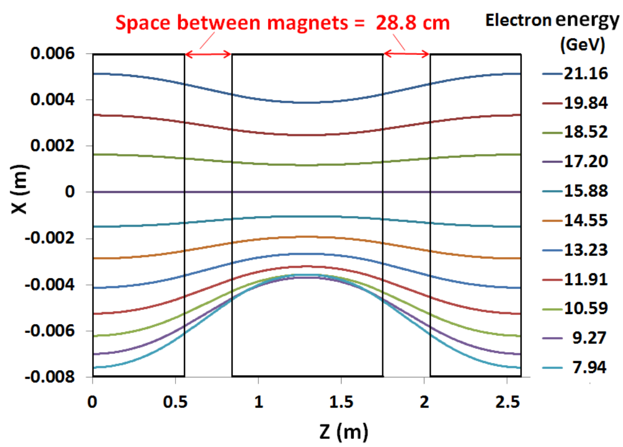

Figure 1: Electron trajectories in one cell of the high energy FFAG beam transport [1].

Here we have started to address these issues by performing Particle Studio [3] simulations for two preliminary designs of possible BPM configurations, one based on a set of conventional "button" pickup electrodes (PUEs) and the other one on a new design of tapered stripline PUEs designed in an attempt to mitigate an additional challenge, namely the result of sample timing errors. This last problem is particularly severe when closely-spaced bunches make it impossible to use conventional filters [4] with long enough time constants so as to provide pulse maxima that are flat enough to be accurately sampled and digitized.

DESCRIPTION OF THE MODELS

The two models used for the Particle Studio simulations are shown in Figs. 2 and 4. In both cases, the left and right tubular parts of the vacuum chamber cross sections will have cooled walls to absorb the power generated by the intense synchrotron radiation.

The tapered striplines shown in Fig. 4 are designed to receive a linearly increasing and decreasing induced charge as the "pancaked shaped" (Lorentz-contracted)

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electromagnetic field traverses over them. The output current from one of these pick-up electrodes, which is proportional to the derivative of these induced charges, will therefore show relatively flat portions amenable to accurate digitization without the use of additional filters. To what extent this can be achieved will be indicated by the simulation results shown in the next section.

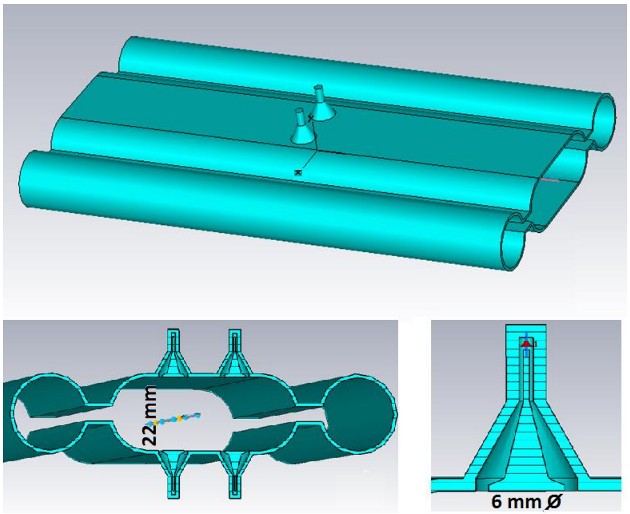

Figure 2: Model used for the Particle Studio simulations of a BPM consisting of four 6 mm diameter button-type PUEs. The unusual positions are chosen so as to allow synchrotron radiation to escape and also to accommodate the ± ~5 mm horizontal orbit locations.

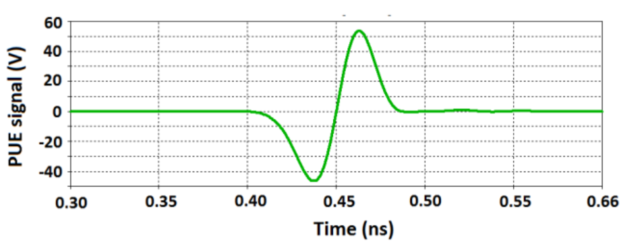

Figure 3: Particle Studio simulated button type PUE signal generated on a 50 Ω load for a centered, 4 mm rms long fully relativistic (v=c) bunch containing 3.1E10 electrons (~ 5 nC).

As mentioned above, the conventional configuration of two horizontal and two vertical PUEs cannot be implemented for this application. What is also unusual is that the design orbits are not horizontally centered. The two quantities that will be computed in this case to measure the horizontal and vertical positions will each necessarily contain all four voltage values obtained from the PUEs. Naming these values UL, UR, DL and DR, where U stands for up, D for down, L for left and R for right we will calculate the ratios Qx and Qy as most indicative of the horizontal and vertical position respectively:

$$\boldsymbol{Q_x} = \frac{(UL+DL)-(UR+DR)}{UL+UR+DL+DR} \quad \text{and} \quad \boldsymbol{Q_y} = \frac{(UL+UR)-(DL+DR)}{UL+UR+DL+DR}$$

The sum of the four signal amplitudes in the denominators provide the required intensity normalization. How these quantities correlate with the actual positions will be determined below from the simulations. Experimental calibrations would be performed for an actual system to allow the determination of real positions.

The simulated signal amplitude response for the button BPM is shown in Fig. 3 assuming bunch parameters of the FFAG-based eRHIC design. For detection of the pilot bunches the signals the PUE signals will be filtered and sampled using conventional electronics as described for example in Reference [4].

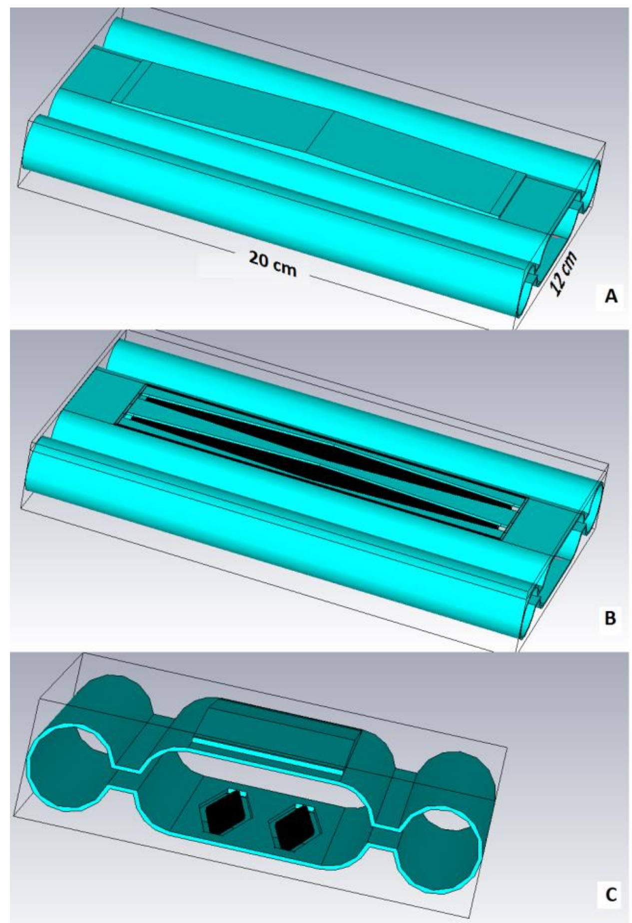

Figure 4: Model used for the Particle Studio simulations of a BPM consisting of four tapered striplines. A) External view. At the top, one sees the inclined ground plane used to maintain the stripline's 50 Ω impedance in spite of its varying width. B) The top ground plane has been removed and one sees the two top tapered striplines (black). C) End view showing the two bottom striplines.

SIMULATED RESPONSES OF THE TAPERED PUEs

The Particle Studio simulations were performed with the model shown in Fig. 4 using a 12 ps rms bunch containing 3.1E10 electrons which corresponds to a

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charge of ~5 nC. The trajectory positions were varied in 1 mm steps from -6 to 6 mm horizontally (x direction) and from 0 to 3 mm vertically (y direction). The signals from one of the PUEs as functions of x are shown in Fig. 5 for y=0. The short positive and negative peaks seen in the signals (see Fig. 5) are due to the fact that the PUEs cannot end in sharp points. In fact these 150 mm long PUEs are 10 mm wide in the center and 1mm wide at their ends.

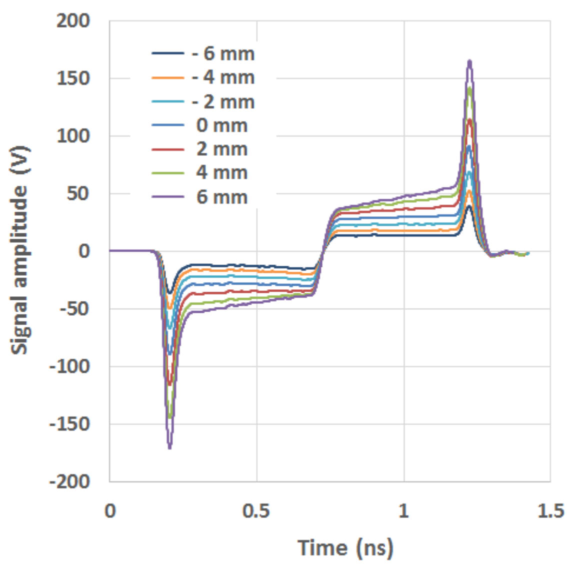

Figure 5: Simulated signals generated on a 50 Ω load connected to one end of one of the PUEs shown in Fig. 4 for vertically centered bunches containing 3.1E10 electrons (~5 nC). The horizontal orbit positions are varied from -6 mm to +6 mm in 1 mm steps.

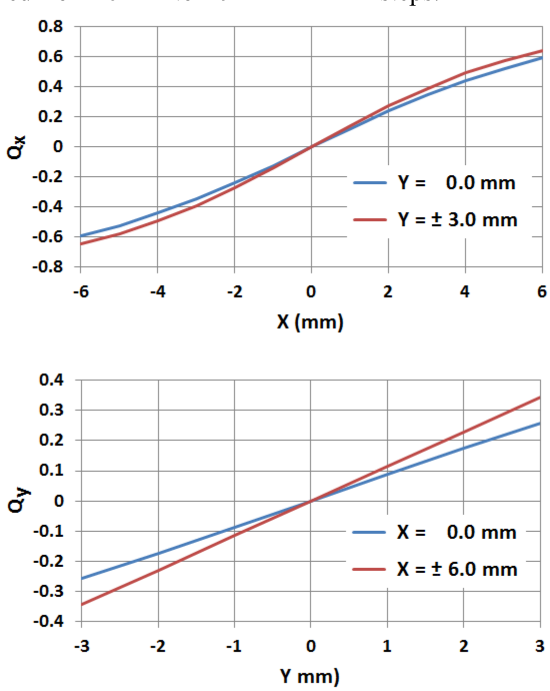

Figure 6: Horizontal (top) and vertical (bottom) calibration curves obtained from the simulations when the orbit was either centered or at its extreme position in the other plane.

Figure 6 shows calibration curves obtained by using the quantities Qx and Qy defined above, calculated by using the pulse amplitudes at the centers of the relatively flat negative portions of the signals (see Fig. 5). For each of these cases we show two calibration curves; one with the trajectory centered in the other plane and the second one with the trajectory at its extreme position in the other plane

We see from Fig. 6 that the ***x***-calibration depends on the value of ***y*** and vice versa. This can be seen in a more comprehensive way in Fig. 7 which shows the mapping of the ***Qx*** and ***Qy*** values onto the corresponding ***x*** and ***y*** coordinates

The mapping "pincushion" distortion shown in Fig. 7 is also present for other types of BPMs. In the present case it is particularly important to take into account two-dimensional mapping since some of the nominal orbits are horizontally displaced by as much as ± ~5 mm.

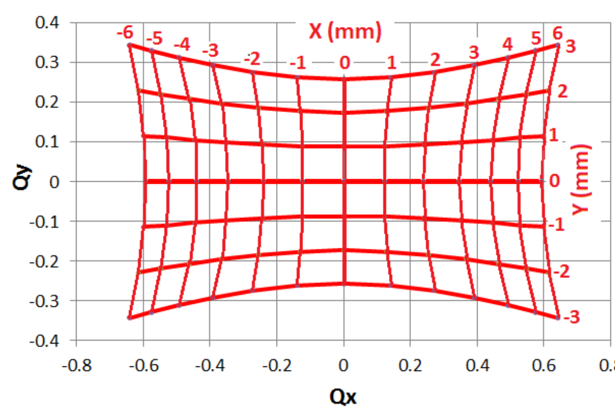

Figure 7: Mapping of the ***Qx*** and ***Qy*** ratios calculated from the tapered stripline PUE signal amplitudes (see text) onto the corresponding ***x*** and ***y*** beam position coordinates.

POSITION MEASUREMENT SENSITIVITY TO TIMING ERRORS

The slopes of the signals shown in Fig. 5 increase gradually as the horizontal distance from the center increases. These slopes will result in measurement errors if there are sampling-time fluctuations. The sensitivities to sampling-time errors are shown in Figs. 8 and 9. Figure 8 shows this sensitivity as function of horizontal position obtained using the simulated data of Fig. 5 by sampling values of the negative part of the pulses (blue points) and of the positive part (red points). The slope of the signals are of opposite sign and therefore the errors at each value of x are opposite too. These calculations were performed assuming a sampling time length of 100 ps and thus averaging the values between 0.4 and 0.5 ns for the negative part and between 0.9 and 1.0 ns for the positive one. Then both of these intervals were shifted by 10 ps to establish the timing sensitivity.

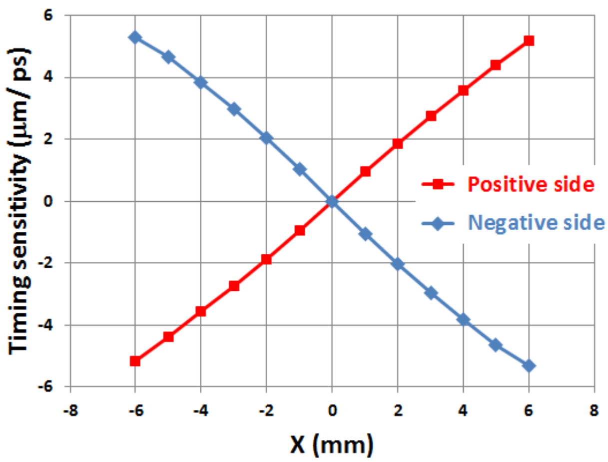

Figure 8: Sensitivity of simulated horizontal position measurements to sampling-time fluctuations. These relatively small time dependences are due to the slope of the positive and negative portions of the pulses seen in Fig. 5.

The worst cases (for large x values) of ~5 μm per ps are similar to values observed with regular BPMs and much longer bunches. Averaging these two position results at each value of x largely eliminates the sampling time sensitivity providing the sampling time errors are common to both measurements. The residual sensitivities of these average positions are shown in Fig. 9.

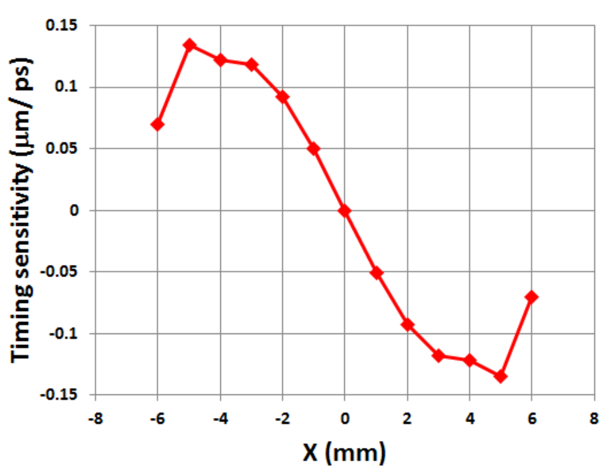

Figure 9: Residual timing sensitivity of positions obtained by averaging values obtained by sampling negative and positive parts of the signals shown in Fig. 5 (see text).

CONCLUSIONS

The multiple eRHIC electron orbits in the proposed lattice of the Non-Scaling FFAG spread out horizontally over ± 5 mm, and the presence of intense synchrotron radiation requires a somewhat unusual BPM PUE configuration. We have shown how positions can be obtained for such configurations and we have analyzed in detail the type of two-dimensional measurement distortions that will need to be corrected in software.

For the extremely short eRHIC electron bunches, the tapered stripline BPM could, at least in principle, generate signals amenable to accurate sampling and digitization without the use of conventional filters. This may allow accurate position measurements of bunches separated by as little as 2 ns for the present design. The major issue that hasn't been addressed here is how the performance will be affected by the coaxial cable response if the digitizer can't be located very close to the BPM.

A possible alternative to the tapered stripline BPM that has not been investigated in detail is a BPM based on straight (not tapered) striplines used in conjunction with signal integrators. Yet another possible modification of both of these designs would consist in replacing the "floating" PUEs considered here with ones half as long and grounded at one end. The calibration issues for all of these alternative designs would be the same as studied here. Experiments as well as further simulations will be required to make progress towards a final design.

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