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MEASUREMENT OF CRABBING ANGLE WITH PHASE INFORMATION FROM BPM*

I. Pinayev†, Brookhaven National Laboratory, Upton, NY, USA

Abstract

The Electron-Ion Collider is being constructed at the Brookhaven National Laboratory. The crab cavities will be utilized for the increase of the luminosity. While the initial set-up of crab cavities can be based on the orbit measurements during dedicated development time, we need to utilize a less invasive approach for monitoring the longitudinal beam tilt during operations. We propose to measure a phase shift between two beam position monitor channels for this purpose. The signal can be easily incorporated into the RF system feedback to suppress noise in the system. Theoretical considerations as well as tests with the electron beams are presented.

INTRODUCTION

Electron-ion collider will employ multiple transverse deflecting (crabbing) cavities to increase luminosity [1].

For proper compensation of the crossing angle each crab cavity should individually calibrated and phased. At KEK the crabbing angle was measured with the beam displacement [2] depending on the crab-cavity phase. The amplitude of orbit deviation is used for the kick calibration, and the two settings for zero crossings separated by 180 degrees provide information for the phase shift.

During regular operations the scanning of the crab cavities is not possible, and we need to develop alternative method.

THEORETICAL CONSIDERATIONS

In [3-6] it was proposed to measure the longitudinal tilt using phase information from BPM signals. Following the calculations in [6] we can find the phase shift between two electrodes. Charged induced by relativistic beam with gaussian profile on the buttons A (top) and B (bottom) can be described by formulas [7]:

$$Q_A(t) = \frac{qQ_{bunch}}{\sqrt{2\pi}c\sigma}\left(1 + S(y + \alpha ct)\right)exp\left(-\frac{t^2}{2\sigma^2}\right), \\ Q_B(t) = \frac{qQ_{bunch}}{\sqrt{2\pi}c\sigma}\left(1 - S(y + \alpha ct)\right)exp\left(-\frac{t^2}{2\sigma^2}\right), \tag{1}$$

where Q_{bunch} is bunch charge, q characterizes pick-up geometry (like the ratio of button area to pipe diameter), σ is bunch length, S is a BPM scaling factor, y is the position of the bunch center (deflection is in the vertical plane), α is a crabbing angle, c is the speed of light. Here we assume that the induced charge is proportional to the bunch linear charge density ($r/\gamma c \ll \sigma$, where r is vacuum chamber radius and γ is a relativistic factor).

The varying button charge will induce a voltage on the cable with impedance Z (neglecting button capacitance). The cosine and sine components can be found using Fourier transformation at the observation angular frequency ω, which might be harmonic of the repetition frequency.

$$U_{cosA,B} = \frac{2}{T}\int_{-T/2}^{T/2} U_{A,B}(t)\cos\omega t\, dt\,, \\ U_{sinA,B} = \frac{2}{T}\int_{-T/2}^{T/2} U_{A,B}(t)\sin\omega t\, dt\,. \tag{2}$$

For the short bunches ($\omega \ll T$) the integral limits can be extended to infinity, and the integral can be calculated analytically.

$$U_{cosA,B} \approx \pm\frac{2}{T}ZqQ_{bunch}S\alpha\sigma^2\omega^2 e^{-\frac{\omega^2\sigma^2}{2}}, \\ U_{sinA,B} \approx -\frac{2}{T}\frac{ZqQ_{bunch}}{c}(1 \pm Sy)\omega e^{-\frac{\omega^2\sigma^2}{2}}. \tag{3}$$

In case of small beam displacements ($Sy \ll 1$) the phases of the signals will be

$$\varphi_{A,B} = \pm\cot^{-1} cS\alpha\sigma^2\omega\,. \tag{4}$$

For small crabbing angles the phase shift between two channels will be

$$\varphi_B - \varphi_A = 2S\alpha c\sigma^2\omega_{BPM}\,. \tag{5}$$

EXPERIMENTAL SET-UP

Experimental measurement of the longitudinal beam tilt in [6] showed factor two difference between theoretical and observed values of the phase shift. Such large discrepancy required additional investigation to find a source of error. This is also essential since the vertical tilt was developed using fast kicker installed in the region with non-zero dispersion [8].

There are two transverse deflecting cavities available at the C-AD complex for the test of the proposed method. The first one is installed in the Coherent electron Cooling (CeC) experiment, and the second cavity is used by Low-energy RHIC electron Cooling (LEReC). Both cavities are intended for measurement of the longitudinal profile. We can monitor beam size (current profile and bunch length) for both setups during measurements. The longitudinal tilt can be estimated from the vertical r.m.s. beam size (assuming that the emittance contribution is small) and r.m.s. bunch length. It can be also calculated from deflecting cavity

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† pinayev@bnl.gov

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parameters (U_{cav} and ω_{cav}), beam rigidity pc and distance L from the cavity to the BPM.

$$\alpha = \frac{U_{cav}}{pc}\frac{L\omega_{cav}}{c}. \tag{6}$$

After the substitution into the Eq. (5) we obtain

$$\varphi_B - \varphi_A = 2SL\frac{U_{cav}}{pc}\sigma^2\omega_{cav}\omega_{BPM}\,. \tag{7}$$

Both systems have Libera Single Bunch BPM [9] with a bandpass filter ringing on the known frequency. The raw ADC data are available for analysis and sample of data is shown in Fig. 1. The ADC sampling rate and hence phase advance per clock tick are also known. Only the central part of the waveform was used for fit, described by the formula below, and the phase φ in the fit was used for the measurements

$$U(t) = A(1 + at + bt^2)\sin\omega t + \varphi\,. \tag{8}$$

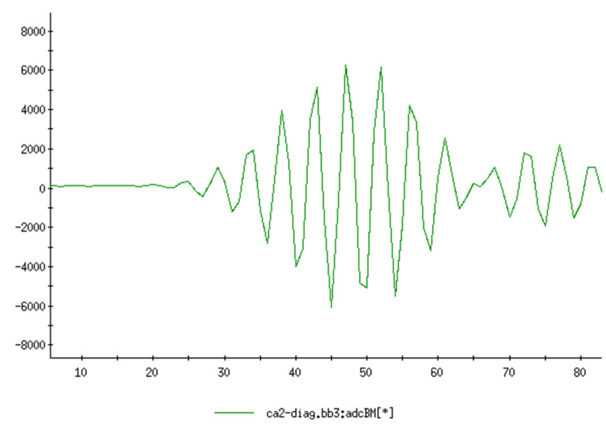

Figure 1: The raw ADC signal from one channel.

For LEReC the electron beam energy is E_{kin} = 1.58 MeV (γ = 4.1, pc = 2.03 MeV). 704 MHz deflecting cavity has 50 kV max voltage. BPM is tuned to 704 MHz ($\omega = 4.42\times10^9$) and has scaling factor S = 53 m^{-1} (k = 19 mm). Distance from the cavity to BPM is 0.43 m, and to the screen is 1.96 m.

The longitudinal profile of the LeREC bunch current is shown in Fig. 2. The profile is close to the gaussian shape with r.m.s. bunch length of 32.7 ps.

The dependence of the phase shift on the deflecting cavity voltage is shown in Fig. 3. Using Eqs. (6) and (8) we can estimate that bunch longitudinal tilt at the location of BPM will be 124.8 mrad for 40 kV cavity voltage, and corresponding phase shift is 18.8 mrad.

For CeC beam energy is Ekin = 14.05 MeV (γ= 28.5). The 1.3 GHz deflecting cavity has 100 kV maximal voltage. BPMs are tuned to 500 MHz ($\omega = \pi\times10^9$), distance from the cavity to BPM2 is 2.73 m with scaling factor S_2 = 64.9 m^{-1} (k = 15.4 mm), distance from the cavity to BPM3 is 4.64 m with scaling factor S_3 = 46.7 m^{-1} (k = 21.4 mm). Distance from cavity to the profile monitor is 4.92 m.

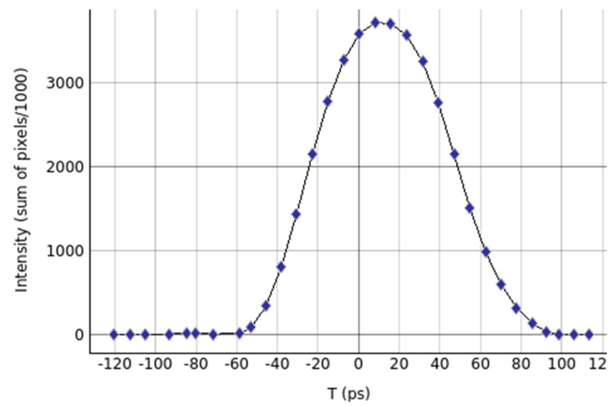

Figure 2: Longitudinal profile of the LeREC electron beam. The shape is close to gaussian with FWHM equal to 77 ps.

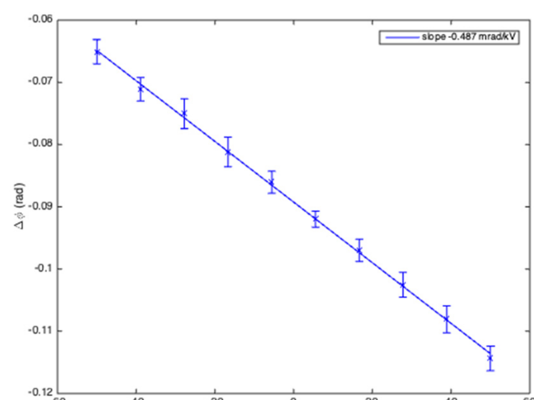

Figure 3: The measurement of the longitudinal tilt with LeREC deflecting cavity. R.m.s. bunch length is 32.7 ps. The phase shift between BPM channels is about 19.5 mrad for 40 kV cavity voltage (estimate is 18.8 mrad).

The CeC bunch current profile is not gaussian as it is shown in Fig. 4, and we need do develop new equations for calculating the expected phase shift. The amplitude of the induced signal on the button is proportional to the derivative of the longitudinal bunch charge density.

$$U(t) \sim \dot{q}(t) = \frac{1}{c}\frac{dI(t)}{dt}. \tag{9}$$

After integration by parts and taking into the account that current density is zero at infinity, we get Eq. (10).

$$\begin{aligned} U_{cosA,B} &\sim -\int_{-\infty}^{\infty} I(t)[\pm S\alpha c\cos\omega_{BPM}t - \omega_{BPM}(1 \pm S\alpha ct)\sin\omega_{BPM}t]dt\,,\\ U_{sinA,B} &\sim -\int_{-\infty}^{\infty} I(t)[\pm S\alpha c\sin\omega_{BPM}t + \omega_{BPM}(1 \pm S\alpha ct)\cos\omega_{BPM}t]dt\,. \end{aligned} \tag{10}$$

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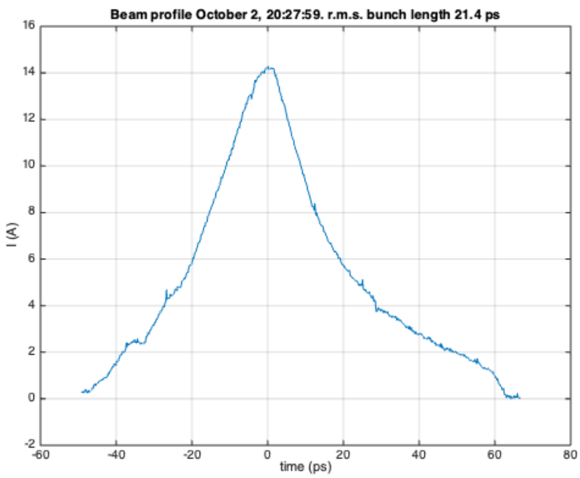

Figure 4: CeC bunch current profile.

The formulas in the Eq. (10) can be utilized in the script using numerical integration of the current profile data from the screen for calculation of the phase shift. 75 kV voltage of the deflecting cavity provides longitudinal tilt of 0.383 radians for BPM2 and 0.651 radians for BPM3.

The dependence of the phase difference between two channels son the deflecting cavity voltage is shown in Fig. 5. For the shown current profile the phase shifts are expected for the BPM2 25.6 mrad and for the BPM3 38.8 mrad. The measured phase shifts are 26.5 and 33.5 mrad, respectively.

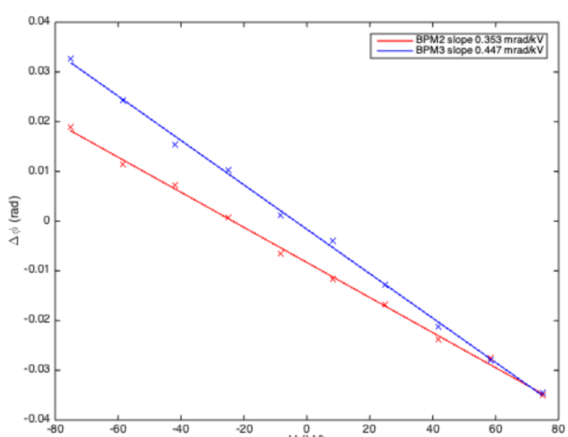

Figure 5: The dependence of the phase shift on the deflecting cavity voltage.

CONCLUSION

The proposed method can be used for monitoring the crabbing angle using the pick-up electrodes located inside the interaction region. Pick-up electrodes outside the interaction region can be used for monitoring the crab angle closure as well as for feedback on the crab cavity RF system for preventing emittance growth [10, 11].

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