Diagnostics of Interaction Point Properties and Bunch-by-Bunch Tune Measurements at CESR*

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Abstract. The Cornell Electron Storage Ring (CESR) undergoes significant changes in running conditions as operation for CLEO-c high energy physics is interleaved with synchrotron light operation for CHESS (Cornell High Energy Synchrotron Source). Two examples of CESR beam instrumentation applications that are being used to understand storage ring conditions are described: 1) measurement of coupling at the interaction point using the single bunch, multiple turn, type I CESR Beam Position Monitor (CBPM) electronics with continuous beam excitation and 2) measurement of individual bunch tunes to explore possible electron cloud effects using the multiple bunch, multiple turn, type II CBPM electronics with a shock-excited beam. Both applications use the same acquired data for a given bunch, which is turn-by-turn beam position data, and both applications extract the relevant information using the discrete Fourier transform of the time sequences.

Keywords: CESR, CLEO, CHESS, storage ring, beam position monitor, CBPM, betatron tunes, coupling, interaction point, luminosity, e+, e-, collider, electron cloud.
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INTRODUCTION

Two applications will be described that use multiple-turn beam position data made practical due to the development of the wideband CESR Beam Position Monitor (CBPM) system [1,2]. The CBPM system provides the capability to sample the beam position on a bunch-by-bunch, turn-by-turn basis by sampling individual beam buttons at several detectors in CESR. The raw button data is read back and archived for both immediate and later analysis. The two applications described here extract the desired information using the discrete Fourier transform (DFT). Both applications use 1024 turns of position data for each bunch. This number of samples makes it convenient to use the Fast Fourier Transform algorithm.

The first application uses measurements at the two beam position monitors (BPMs), which are adjacent to the IP (interaction point) to measure coupling in order to calculate the coupling at the IP. This application is relevant to the CLEO-c colliding beam experiment. Gain calibration for the beam buttons is critical and the method will be described here.

The second application measures the tunes of all bunches simultaneously which will be useful in the study of possible electron cloud effects.

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CESR Background

The Cornell Electron Storage Ring (CESR) has been used for both colliding beam high energy physics (HEP) and for CHESS (Cornell High Energy Synchrotron Source) synchrotron light experiments for more than 25 years. The dual use has been simultaneous until recently. The highly successful B-physics operation at beam energies suitable for CHESS has been supplanted by alternating modes of operation whereby the storage ring is switched between CLEO-c HEP operation at energies in the range of 2.0 GeV and CHESS operation at 5.3 GeV.

Since the two modes are now exclusive, performance expectations for each have been even higher than in the past. Furthermore, changing conditions from one mode of operation to the other is expected to be routine. The CBPM system is expected to contribute to high performance under changing operation conditions.

CBPM System Description

The CBPM system [1,2] is comprised of the CESR beam detectors, the timing distribution system, the electronics modules for sampling the detector signal and the software for configuring and reading out the data from the electronics modules.

The beam detectors nearest the CESR IP are of interest here for the first application. They are in a chamber with circular cross-section. The four beam button signals from a detector are sampled by the CBPM module.

Timing information is provided to the CBPMs in the CESR tunnel by a pair of RG214 coaxial cables with a video coupler at each CBPM module. The signal consists of a 24 MHz clock signal with encoded betatron phase and trigger information. A particularly important capability of the system is that the acquisition trigger can be made synchronous with the 60 Hz power line, because in CESR the betatron tunes are sometimes modulated much more in one 60 Hz cycle than the variation being investigated for other reasons. It should also be noted that different modules are all triggered with respect to each other with precision much better than one turn.

Modules have two types, designated I and II. Common attributes are at least one channel per beam button. Each channel has an attenuator and filter, followed by a variable gain video amplifier that feeds an ADC (analog-to-digital converter). A channel samples one button signal.

The type I CBPM module has the capability to sample a single bunch at a time over multiple turns. Fourteen (14) of these modules have been deployed and they are typically used to measure orbit and betatron phase at those locations. A different set of timing values must be loaded if, for example, an electron bunch is to be sampled versus a positron bunch. The type I ADCs are clocked at 390 kHz, or once per turn.

The type I module is often used in applications where the beam is not excited or is excited in CW (continuous wave) mode using the tune tracker, which measures the beam using a phase-locked loop and which locks on to the motion by shaking the beam at the betatron tune(s), thereby generating a signal that is locked to the tune.

The type II module has the capability to sample all 183 possible electron (e-) and positron (e+) bunches at the same time. There are two interleaved 72 MHz ADC clocks. This capability is crucial to measuring the tunes of a single long train of shock-excited bunches as is done in the second application. For the type II module, the timing is a single value for a specified first bunch and a CESR fill pattern specifies the other bunch timings.

COUPLING MEASUREMENTS AND PROJECTION TO THE IP

For the CESR-c colliding beam experiment, achieving and maintaining high luminosity involves, among many other things, maintaining small beam height at the IP. In addition to achieving small emittance in the storage ring, the coupling between the horizontal and vertical planes is critical to obtaining minimum beam sizes.

One of us (Temnykh) developed a method for measuring and visualizing IP coupling in the following manner. The beam is shaken hard at the horizontal tune and 1024 turn position data at beam detectors designated 0W and 0E, adjacent to the IP, are taken using the type I CBPM modules located there. The detector data is projected to the IP and the IP coupling is calculated.

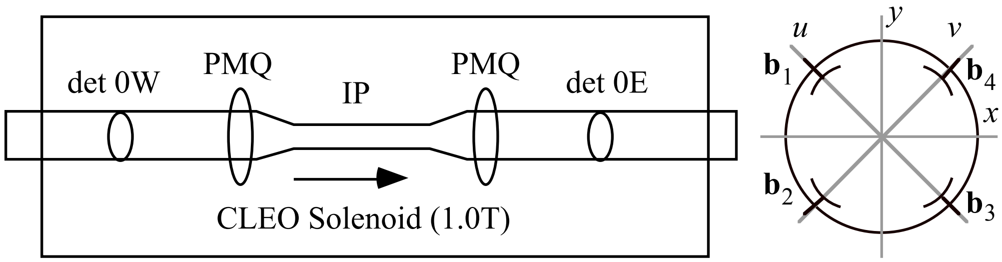

FIGURE 1. LEFT. Simplified schematic of CESR interaction region (IR). **RIGHT.** Detector shape.

Projecting Measured Transverse Position Data to the IP

Given the transverse angle and position vectors at the two detectors and at the IP:

$$\bar{x}^T = \begin{pmatrix} x & x' & y & y' \end{pmatrix} \tag{1}$$

and well-defined transport matrices M which include the CLEO solenoid and the rotated permanent magnet quadrupole (PMQ) magnets such that:

$$\bar{x}_{ip} = M_w \bar{x}_w \quad and \quad \bar{x}_e = M_e \bar{x}_{ip} \tag{2}$$

then:

$$\bar{x}_e = M_{tot} \bar{x}_w, \quad M_{tot} = M_e M_w \tag{3}$$

The relations in (3) provide for a solution to the angles since all four x and y positions for each data point have been measured. Defining the unknown angle vector a:

$$\bar{a}^T = (x'_w \quad y'_w \quad x'_e \quad y'_e) \tag{4}$$

and given the known difference vector $\bar{x}_{diff}$ and known matrix A:

$$\bar{x}_{diff} = \begin{pmatrix} x_e - m_{1,1}x_w - m_{1,3}y_w \\ -m_{2,1}x_w - m_{2,3}y_w \\ y_e - m_{3,1}x_w - m_{3,3}y_w \\ -m_{4,1}x_w - m_{4,3}y_w \end{pmatrix} \quad and \quad A = \begin{pmatrix} m_{1,2} & m_{1,4} & 0 & 0 \\ m_{2,2} & m_{2,4} & -1 & 0 \\ m_{3,2} & m_{3,4} & 0 & 0 \\ m_{4,2} & m_{4,4} & 0 & -1 \end{pmatrix} \tag{5}$$

then:

$$\bar{x}_{diff} = A\bar{a} \quad or \quad \bar{a} = A^{-1}\bar{x}_{diff} \tag{6}$$

The $m_{i,j}$ are elements of M_{tot}. Using the first half of (2) to obtain the projection to the IP from the measured positions and calculated angles at detector 0W:

$$\bar{x}_w^T = (x_w \quad a_1 \quad y_w \quad a_2) \longrightarrow \bar{x}_{ip} = M_w \bar{x}_w \tag{7}$$

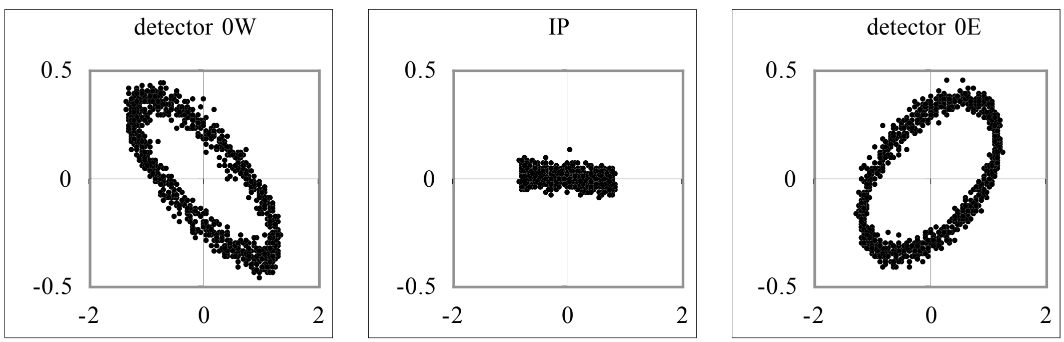

FIGURE 2. 1024 turn, y versus x data (in mm) measured at adjacent detectors and projected to the IP.

Fitting the Ellipse to Calculate Coupling

Although a plot of the raw x versus y data may appear to be noisy, the fact that it should describe an ellipse is used to advantage. The amplitude and phase of the motion can be extracted using the discrete Fourier transforms because the ellipse is representative of coherent motion in both planes at the same frequency [3].

The signal amplitudes are calculated by summing the energies in the spectral lines within seven frequency bins on either side of the peak. The phase of the signals is obtained from the phase of the maximum frequency component. For real time sequences $x(n)$ and $y(n)$ and their discrete Fourier transforms $X(k)=X_r(k)+jX_i(k)$ and $Y(k)=Y_r(k)+jY_i(k)$ with a single maximum at $k = p$, the amplitudes are:

$$|X|^2 = \sum_{k=p-7}^{p+7} |X(k)|^2 \quad and \quad |Y|^2 = \sum_{k=p-7}^{p+7} |Y(k)|^2 \tag{8}$$

and the phases are:

$$\phi_x = \tan^{-1}\frac{X_i(p)}{X_r(p)} \quad and \quad \phi_y = \tan^{-1}\frac{Y_i(p)}{Y_r(p)} \tag{9}$$

The aspect ratio and angle of the ellipse are given by the out-of-phase and in-phase components of (y/x):

$$(y/x)_{out} = \frac{|Y|}{|X|}\sin(\phi_y - \phi_x) \quad and \quad \theta = (y/x)_{in} = \frac{|Y|}{|X|}\cos(\phi_y - \phi_x) \qquad (10)$$

and the two coupling matrix elements of interest are [3]:

$$\bar{c}_{1,2} = (y/x)_{out}\sqrt{\frac{\beta_x}{\beta_y}} \quad and \quad \bar{c}_{2,2} = \theta\sqrt{\frac{\beta_x}{\beta_y}} \qquad (11)$$

where β_x and β_y are the values of the beta functions at the ring location of interest.

Gain Calibration of the Beam Button Data

The data provided by the CBPM system is not, in fact, position data, rather it is beam button data. The x and y data are expected to be decoupled in the detection process and differences in button gains are significant contributors to errors. Various characteristics of the individual beam buttons and the fact that separate channels are used to measure each button signal make it highly necessary to have a beam-based gain calibration method. If one could produce a condition where the beam was known to be centered in the detector, then the button signals should all be equal and a measurement of the signal values in that case would provide the desired gain calibration.

The nonlinear characteristic of the beam detector with respect to position provides the needed mechanism for determining that the beam is centered. In the case of the CESR beam detectors at 0W and 0E, the beam pipe is of circular cross-section with four beam buttons located symmetrically on the wall. Using the coordinates u and v shown in Figure 1, the normalized signal from beam button 1 can be approximated by:

$$b_1(u)\big|_{v=0} = \frac{r_p + u}{r_p - u} \quad and \quad b_1(v)\big|_{u=0} = e^{-\left(\frac{v}{r_b}\right)^2} \qquad (12)$$

where r_p is the beam pipe radius and r_b is the button radius. The x and y positions derived from these functions are the product of the two.

Calculation can be used to verify that a plot of x versus y describes a parabola over a small range of x and that y is a linear function of the coefficient of x^2. The quadratic coefficient is zero at the center of the beam pipe where x versus y becomes a straight line. This relationship is also borne out by experiment.

Using the difference-of-sums-over-sum method for calculating positions near zero:

$$x = \frac{b_4 + b_3 - (b_1 + b_2)}{\sum b} \quad and \quad y = \frac{b_4 + b_1 - (b_3 + b_2)}{\sum b} \qquad (13)$$

the procedure is to shake the beam to large amplitude in the horizontal plane and take successive data sets as the beam is moved vertically in the detector. Then fit the x versus y data for each set to a parabola and plot the CESR parameter that was used to move the beam, and presumed to be linear in doing so, versus the coefficient for the quadratic term, being careful to establish a standard hysteresis loop in any magnets.

The result is very nearly a straight line so the y-intercept of the plot gives the command that will center the beam vertically. The procedure is repeated using vertical shaking and a horizontal position scan to discover the command that centers the beam horizontally. With the beam centered in both planes, the button signal values are recorded and the button gain corrections are calculated.

While this procedure establishes the button gains, it is also important to correct the position data for the beam detector nonlinearity, since the beam is not normally centered in the detector when the coupling measurement is made. In CESR the position offset is mostly horizontal due to the pretzeled orbit, whereby the opposing beams are arranged in trains that avoid collisions with each other by virtue of systematic horizontal electrostatic separation. A simple quadratic correction suffices in this case. A more general nonlinear correction algorithm is quite necessary if the beam is significantly off-center in both planes [4]. Most of the nonlinearity comes from the second part of (12).

IP Coupling Projection Accuracy

The accuracy of the coupling at the IP as calculated from the measured data at the two adjacent detectors is limited by several items, which are, the physical uniformity and installation accuracy of the beam detectors, the value of the coupling at the beam detectors, the accuracy of the button gains, the accuracy of the nonlinear correction and the signal-to-noise ratios (SNRs) of the measured x and y signals.

The CESR zero detectors are very uniform and the installation angle error is less than 0.5°. The design coupling at these detectors is usually large enough, mainly due to ellipse angle, so that the y signal is only approximately 20 dB lower in amplitude than the x signal. A beam-based button gain calibration is available. Nonlinear button correction for converting to position is vital.

To obtain enough signal, it is almost always necessary to reduce the CESR transverse feedback gains. It is desirable to have at least 30 dB SNR in x and 10 dB SNR in y. With these criteria, aspect ratios at the IP can be reasonably calculated up to values of 150 and to relative angles of the two beams within 0.5° [5].

TUNE MEASUREMENT

A number of situations arise where knowledge of the betatron tunes of different bunches would be informative. The measurements described in the previous section involve measurement of just a single bunch as sampled by the type I CBPM module, however the analysis technique provides the basis for measuring the tunes of multiple stored bunches using the type II CBPM module. The DFT provides the information necessary to extract the tune and a window function enhances the resolution of the measurement. An excellent treatment of windowing in the absence of noise for the purpose of measuring frequency is provided in [6], although [7,8] provide the source for the technique described here. The logarithm of a Gaussian is a parabola [8].

Measuring Frequency Using the DFT in the Presence of Noise

The revolution frequency in CESR is approximately 390 kHz so 1024 turns of data cover a time span of 2.6 milliseconds and the DFT frequency bins are at 381 Hz intervals. The measurement precision desired is approximately 10 Hz for studying effects such as long-range beam-beam interaction or possible electron clouds to name only two. A 40:1 improvement in resolution is called for.

Using a Gaussian window, the *sin(x)/x* filter characteristic of the DFT becomes more like a Gaussian near the peak, thereby making it suitable to fit the logarithm of the amplitude to a parabola [7,8]. Using a quadratic fit to three points nearest the peak, the optimum window for an N=1024 sample time sequence that includes uniform noise and an exponential decay is a truncated Gaussian with $\sigma = N/4$ centered at N/2. The standard error for such a measurement is approximately 2 Hz or 5 ppm with 40 dB SNR. This assertion is supported by numerical calculation and by measurement.

Calculation of Frequency Fit Error

The first step is to generate a pure sinusoid, calculate the frequency by interpolation and compare it to the precisely known value. The calculation using a Gaussian window with $\sigma = N/4 = 256$ produces an error of less than 1 Hz over the continuum of frequencies between DC and the Nyquist rate. This error is deterministic for a particular frequency. This includes exponential decay down to a time constant of N/4 or 256.

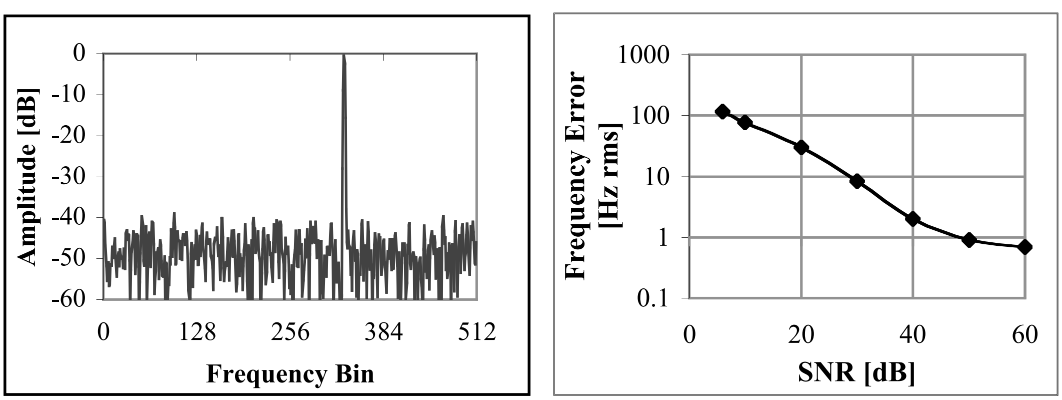

FIGURE 3. Results for an N=1024 point DFT using a truncated Gaussian window with σ = N/4 = 256. **LEFT.** Typical DFT spectrum with 40 dB SNR. SNR is estimated better visually from the noise peaks than from the average. **RIGHT.** Frequency measurement error versus SNR by interpolating with a three-point quadratic fit of the log amplitudes at the peak. A 1 Hz error = 2.5 ppm at 390 kHz.

Next the spectrum is calculated using a signal with noise. The noise is a uniformly distributed pseudo-random number between -1 and 1 scaled to give the noise floor. The right-hand curve in Figure 3 results from putting this calculation through 25 trials for each SNR. A simulated 40 dB SNR spectrum is on the left and it looks just like the real thing.

Measurement of Frequency Fit Error

The type I CBPM system affords a convenient way to check the accuracy of the fitting algorithm. For any measurement, fourteen CBPM modules simultaneously acquire data for a single bunch. Since the tune of a single bunch may be presumed to be the same regardless of where it is measured, correlation of the fourteen measurements provides an estimate of the error.

Table 1 summarizes a series of eleven measurements where the horizontal, vertical and synchrotron tunes of a single bunch were all excited simultaneously and data was acquired simultaneously using all fourteen type I CBPM modules for each measurement [5]. The rms errors are consistent with Figure 3.

TABLE 1. Simultaneous measurement of horizontal, vertical and synchrotron tunes using the fourteen type I CBPM modules. Deviations from the average are shown in Hz rms.

Horizontal Tune ~40 dB SNR	Vertical Tune ~30 dB SNR	Synchrotron Tune ~25 dB SNR
0.5	2.6	10.3
0.3	5.1	5.3
0.9	6.6	6.5
1.1	2.8	11.9
0.6	2.8	10.9
2.5	8.3	7.8
2.4	7.8	9.0
4.7	17.0	19.0
2.9	18.0	11.1
12.2	10.4	23.7
0.3	1.3	11.4

Signal Interference

Extraction of the tunes by measuring the frequency using the DFT can be corrupted in several ways. If two frequencies are very close together, then the technique will not work well at all. An additional problem in CESR is that the tunes are frequency modulated by 60 Hz with a 300 Hz amplitude. Although it might seem wise to increase the number of turns to enhance SNR, this is problematic because in that case the tune is not a well-defined value. It is important to synchronize the trigger with the 60 Hz power line and to acquire data over a time interval that is short compared to the 60 Hz period.

Measuring the Tunes of Each Bunch in a Train

With the tune measurement method in hand, a typical experiment consisted of filling CESR at 5.3 GeV with one train of 45 bunches and acquiring 1024 turns of data for all bunches using the type II CBPM module. In order to measure the tunes separately, CW shaking is inappropriate, since the bunches would all shake at the same frequency. Instead, we shock-excite the beam using the Pinger, a one-turn pulsed magnetic element, and trigger the acquisition synchronously with the Pinger trigger. We adjust the Pinger amplitude to get 30 dB SNR for 10 Hz error whenever we can, without, for example, losing the beam. Figure 4 shows a set of results for an experiment at a beam energy of 5.3 GeV. That experiment continues [5].

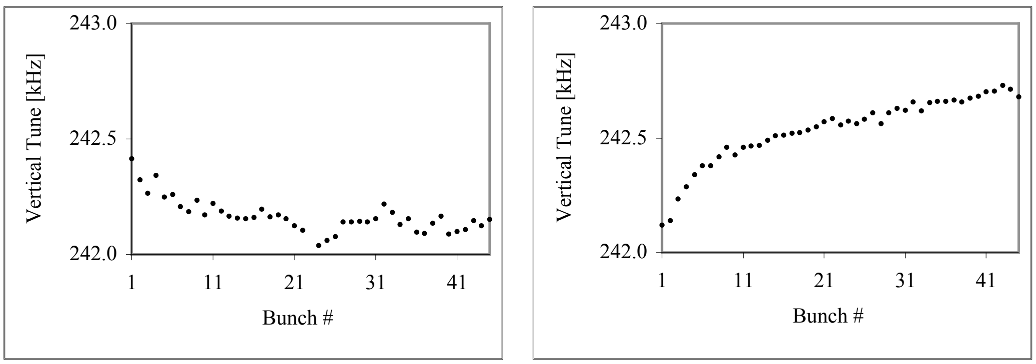

FIGURE 4. Vertical tune versus bunch number for a single continuous train of 45 bunches. **LEFT.** Data for e- showing a small effect. **RIGHT.** Data for e+ showing evidence of electron cloud effect.

CONCLUSIONS

Two significant types of measurements can be made using turn-by-turn beam position measurements. In the first case, data is acquired using multiple detectors for a single bunch. In the other measurement, data is acquired for several bunches by a single detector. The former method may be used to validate the technique used for the second.

Coupling at the IP, especially differential coupling between the two beams, is one measurement that is vital to luminosity in a collider. In order to measure this coupling accurately, we have also shown how to calibrate the beam detector. The detector button data must be linearized.

Bunch-by-bunch tunes can also be measured using the most modern data acquisition hardware whereby all of the bunches in the beam can be measured simultaneously.

Both measurements rely on known signal-to-noise ratio (SNR) for knowledge of accuracy of the measurement. A curve of frequency resolution versus SNR is given for the example of N=1024 turn data at a turns rate of 390 kHz. The frequency is extracted by interpolation using a quadratic fit to the log amplitude of the three highest peaks in the discrete Fourier transform of the position data to which a Gaussian with

$\sigma = N/4$ has been applied. A resolution of 2 Hz or 5 ppm can be obtained with 40 dB SNR if the tune is a well-defined single frequency and there is no nearby interference.

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