DIAGNOSIS OF OPTICAL ERRORS WITH A PRECISION BPM SYSTEM AT CESR

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Abstract

In the Cornell Electron Storage Ring (CESR) multi-bunch beams of electrons and positrons share a common vacuum chamber and guide field. A new precision beam position monitor system, with bunch-by-bunch measurement capability, is now in operation in one sector of the CESR ring including the interaction region (IR). Two of our position monitors are located $67\mathrm{cm}$ on either side of the interaction point (IP) within the 1T experimental solenoid. By measuring the relative positions of electron and positron bunches at these detectors we can obtain information about the displacement of the beams at the collision point with an anticipated resolution on the order of the vertical beam size. The measurement of the dependence of beam trajectories at these IR beam position monitors (IRBPMs) on changes in the ring steering elements provides a powerful diagnostic of guide field errors in the interaction region.

INTRODUCTION

The pretzeled orbits [1] associated with multibunch operation of CESR place the counter-rotating beams off axis in most of the quadrupoles, skew quadrupoles, sextupoles, etc. As a result, skew quadrupoles affect closed orbits differentially for the two beams, and tuning to reduce coupling is complicated by feed down. A new BPM system is capable of precise and nearly simultaneous differential measurement of electron and positron positions near the IP. The relative positions are measured with the requisite resolution to keep the beams in collision. In addition, the dependence of the positions on steering elements outside the IR yields precise determination of coupling parameters.

INTERPOLATION FROM IRBPM TO IP

The transverse phase space coordinates of a trajectory at element i_2 in a ring are given by the transfer matrix [2] M from i_1 to i_2 and the particle's position at i_1:

$$\mathbf{x_{i_2}} = \mathbf{M_{1 \to 2}} \cdot \mathbf{x_{i_1}} \tag{1}$$

Given position measurements at two detectors, and the transfer matrix that propagates the trajectory from one to the other, the orbits are uniquely determined, including at the collision point. Systematic effects are minimized by measuring and mapping electron and positron orbit difference, $\mathbf{\Delta x} = \mathbf{x_{e+}} - \mathbf{x_{e-}}$. The relative positions at the IP are obtained by solving the following system of equations:

$$\mathbf{\Delta x_{ip}} = \mathbf{M_{e \to ip}} \cdot \mathbf{\Delta x_e} \tag{2}$$
$$\mathbf{\Delta x_w} = \mathbf{M_{e \to w}} \cdot \mathbf{\Delta x_e} \tag{3}$$

where $\mathbf{x_e}$ and $\mathbf{x_w}$ and $\mathbf{x_{ip}}$ are the phase space coordinates at the detector just to the east of the IP, just to the west, and at the IP respectively. Between the two IRBPMs are permanent magnet final focus quadrupoles immersed in a 1T solenoidal field for which the mapping is well known. Given the transfer matrices in this region, the determination of the relative IP beam positions and crossing angles is limited only by the resolution of the difference measurement at the IRBPMs.

X-Y COUPLING AT IRBPMS

The positron and electron beams in CESR travel in a pretzel orbit. This pretzel orbit serves to separate the beams at multiple parasitic crossing points around the ring and to establish the horizontal crossing angle at the IP. The experimental solenoid introduces strong x-y coupling in the interaction region so horizontal displacement of the beams in the arcs produces vertical displacement in the IR. This coupling can be parameterized using normal mode coordinates and the $\bar{C}$-matrix [3].

The motion of the normal mode that reduces to the horizontal in a region in which there is no coupling, is given at any BPM by

$$x = A_x \sqrt{\beta_x} \cos n\nu_x \tag{4}$$
$$y = -A_x \sqrt{\beta_y} [\bar{C}_{22} \cos n\nu_x + \bar{C}_{12} \sin n\nu_x] \tag{5}$$

where A_x is the overall amplitude, β_x and β_y are the beta functions at the BPM, ν_x is the normal mode tune, and n is the turn number. By measuring the change in vertical orbit at the IRBPMs due to a change in the horizontal pretzel amplitude, for example by adjustment of the horizontal electrostatic separators, these coupling errors can be determined with good resolution. We take advantage of the difference measurement $(x_{e+} - x_{e-})$ to reduce systematic errors. A similar analysis can be performed using vertical kickers in the ring.

Coupling errors in CESR have traditionally been measured and corrected by taking synchronous phase measurements around the ring and comparing the measurements to the model lattice [4]. Then we adjust machine quadrupoles and skew quadrupoles to minimize the difference between measured and design phase and coupling. This measurement is performed by exciting a beam normal mode with a shaker and monitoring the relative phase and amplitude at each of the BPMs around the ring. It requires that the beam be very nearly centered in all of the beam detectors. Therefore, the separation pretzel is turned off and there is only one beam in the machine. Ideally we would measure coupling corresponding to pretzel trajectories with beams in collision. Guide field nonlinearities and misalignments

introduce pretzel dependent coupling errors that are not accessible by the traditional measurement technique. The coupling measurement based on position dependence in the IRBPMs can yield high resolution about the closed orbits that correspond to colliding beam conditions.

NEW IRBPM DESIGN

A new BPM readout system has been designed and installed in one sector of the CESR ring including the IR [5]. The system is capable of measuring the beam positions of individual bunches and, when operating in its highest precision mode, can cycle between bunches at ~ 100Hz. The system's large bandwidth allows us to resolve counter-rotating bunches at the IRBPMs which pass by at intervals as short as 6 ns. This capability opens up the possibility of monitoring and correcting the trajectories of colliding bunches. In machine studies conditions, we have obtained differential measurements between electron and positron bunches with a resolution of approximately 6μm at the IRBPMs. The system's resolution is limited by ADC and front-end nonlinearities, gain variations between the four independent channels that read out the beam buttons, the timing resolution with which we can digitize the peak of the button signal, and electronic cross-talk between the signals from the most closely spaced bunches.

IRBPM COUPLING MEASUREMENTS

The horizontal separators that generate the pretzel predominantly excite the a or horizontal normal mode. If there is no coupling at the four kickers then the a-mode and x-mode are equivalent and the vertical displacement at the IRBPMs is given by equation 5. Because there is in general finite coupling at the horizontal kickers, the b-mode is excited as well. Therefore, the actual x and y displacement at the IRBPMs is

$$
x = A_a \gamma \sqrt{\beta_a} \cos n\nu_a
$$
$$
+ A_b \sqrt{\beta_a} \left(\bar{C}_{11} \cos n\nu_b - \bar{C}_{12} \sin n\nu_b \right) \quad (6)
$$

and similarly for y. Although the coupling at the kickers is small, the contribution to the change in vertical position due to the b-mode excitation is comparable to the vertical coupling to the a-mode at the IRBPMs so the b-mode contribution cannot be ignored.

The horizontal crossing angle is proportional to the kicks on the 4 horizontal separators that produce the pretzel. The dependence of vertical position versus the horizontal separator kicks is given by

$$
\frac{\partial y}{\partial \alpha} = \frac{\sqrt{\beta_{b_{det}}}}{-2 \sin \pi \nu} \sum_{k=1}^{4} \left(\bar{C}_{22} \sqrt{\beta_{a_k}} \frac{\partial \theta_k}{\partial \alpha} \cos \psi_{a_k} \right.
$$
$$
\left. + \bar{C}_{12} \sqrt{\beta_{a_k}} \frac{\partial \theta_k}{\partial \alpha} \sin \psi_{a_k} \right) + \Phi \left(\frac{\partial A_b}{\partial \alpha} \right) \quad (7)
$$

where the last term represents the component of the slope due to the excited b-mode and $\psi_{a_k} = \phi_{a_{BPM}} - \phi_{a_k} - \pi\nu_a$. Typical Twiss parameters for one of the IRBPMs yield (in μm/mrad)

$$
\frac{\partial y}{\partial \alpha} = 1554 \bar{C}_{22} + 1666 \bar{C}_{12} + \Phi \left(\frac{\partial A_b}{\partial \alpha} \right) \quad (8)
$$

With an anticipated IRBPM resolution of a few microns, variation of crossing angle by 1 mrad gives a resolution on $\bar{C}_{22}$ and $\bar{C}_{12}$ of ~ 0.001. (The typical colliding beam crossing angle is ~ 3mrad.) The resolution of the traditional synchronous phase measurement is 0.01.

A useful characterization of the coupling is in terms of the slope of the measured positions at the IR detectors versus crossing angle. The measured slope is then compared with the machine model. As an example we consider the coupling introduced by vertical misalignment of the ring sextupoles. We misalign all of the ring sextupoles according to a Gaussian distribution defined by $\sigma \sim 200\mu$m and with a 2σ cutoff. We can compute both the change in $\bar{C}_{12}$ at all of the beam detectors, and the change in the slope of y versus θ^* at the IRBPMs. We find that the change in $\bar{C}_{12}$ is of order 0.01 and just about at the resolution limit of the synchronous coupling measurement. But the change in slope corresponds to position changes of 28μm for $\theta^* \sim 1mrad$. With a position resolution of about 6μm, the change in slope due to the coupling introduced by the sextupole misalignment is easily measured.

Coupling Correction using Skew Quadrupoles

To improve the quality of our model of machine coupling we propose to complement the traditional synchronous phase measurement data with measurements of the response matrix at the IR beam position monitors. The CESR ring includes 12 pairs of skew quadrupoles distributed symmetrically around the ring. We find that we can fit position data and phase and coupling data simultaneously with suitable adjustment of the corrector skew quadrupoles. A Levenberg-Marquardt optimization routine is then used to adjust the skew quadrupoles so that the CESR ring model reproduces the measurements. We plan to load the computed skew quadrupole strengths into CESR and then iterate the process. A similar technique, based exclusively on the synchronous phase data [4] has proved quite successful correcting optical errors in the machine arcs, but not so in the IR where, because of the very strong focusing and complicated solenoid compensation, additional constraints are required.

As an example of the leverage of the position measurement in resolving coupling errors we first make a synchronous measurement of phase and coupling around the ring. A comparison of the data $\bar{C}_{12}$ and fitted model is shown in Figure 1. The model is based on a fit to the measured coupling data, using skew quadrupoles as fit parameters. After completing the coupling measurement, and without changing machine conditions, we measure the ver-
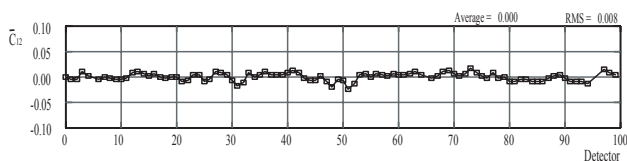
Figure 1: Difference between measured and modeled $\bar{C}_{12}$. The fit is based on the measured coupling $\bar{C}_{12}$ data.

tical position at the IRBPMs versus crossing angle by varying horizontal separator strengths. The data for the west IRBPM is shown in Figure 2. Meanwhile we can predict the position dependence based on the machine model that was used to predict the coupling parameters $\bar{C}_{12}$ shown in Figure 1. The inconsistency of the prediction and the measurement is clear.
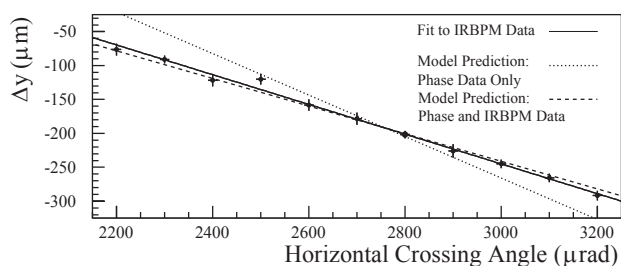

Figure 2: Data points indicate measured differential (positron minus electron) vertical position versus horizontal crossing angle. The solid line is a fit to the data. The dashed line is the model prediction based on a fit to both coupling data and position data. The dotted line is the model prediction based on a fit only to coupling data.

The next step is to try to find a new model that reproduces the position dependence as well as the coupling data. We fit to position data and coupling data simultaneously, again using skew quadrupoles as fit parameters as shown in Figure 2. Note the excellent agreement with the data. The difference between predicted and measured coupling data is shown in Figure 3. The fit of modeled to measured data in Figure 3 is as good as the fit in Figure 1. But the model used in Figure 3 also reproduces the position data. Evidently, the measurement of position at the IR detectors can be used to remove the degeneracy in the modeled machine coupling and to reduce coupling errors at the collision point.
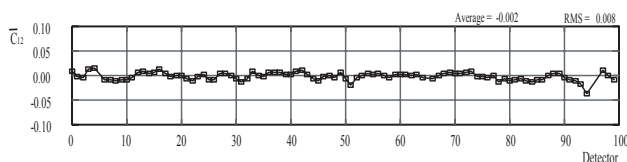

Figure 3: Difference between measured and modeled $\bar{C}_{12}$. The fit is based on the measured coupling $\bar{C}_{12}$ data and the IRBPM position dependence.

Measured dependence of vertical position at the IR detectors on horizontal excitation of kickers helps remove the uncertainty in the coupling in the interaction region. We plan to extend the measurement and fitting procedure to include dependence of horizontal position on vertical excitations so that we can remove the remaining degeneracy in the machine model. With a unique model of the coupling optics we can systematically remove the optical errors in the interaction region that limit performance.

COLLISION ASSURANCE

Having corrected the coupling we would like to develop the capability to monitor relative displacement of the beams at the IP by interpolation from the pair of IRBPMs. As described above, it is straightforward to extrapolate horizontal and vertical position differences measured at the detectors to the interaction point. The measurement resolution of the detectors at present is about 6μm which corresponds to an uncertainty of also about 6μm in the relative positions at the IP or about one and a half times the vertical beam size ($\sigma_y^* \sim 4\mu$m). We expect that with better understanding of the systematics and implementation of improvements to the electronics described above, that a resolution of a fraction of the beam size can be obtained.

CONCLUSIONS

The traditional method of synchronous phase measurement for characterizing optics in CESR lacks the resolution to adequately identify transverse coupling errors at the collision point. The measurement requires a single beam on axis, rather than along the design pretzel trajectory. In addition, because only one element of the coupling matrix is measured, the fitted model is degenerate. The new high resolution beam position monitors yield a measurement of the response matrix with an order of magnitude better resolution and the redundancy necessary to remove this degeneracy. We anticipate that the new system will give a unique determination of the coupling in the IR.

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