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COMMISSIONING THE FAST LUMINOSITY DITHER FOR PEP-II*

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Abstract

To maximize luminosity, a feedback system adjusts the relative transverse (*x, y*) position and vertical angle (*y′*) of the electron and positron beams at the interaction point (IP) of PEP-II. The original system sequentially moved ("dithered") the electrons in four steps per coordinate. Communication with DC corrector magnets and field penetration through copper vacuum chambers led to a 9-s cycle time. Machine tuning can shift the beams at the IP, and so must be slowed to wait for the feedback. The new system simultaneously applies a small sinusoidal dither to all three coordinates at three frequencies. Air-core coils around stainless-steel chambers give rapid field penetration. A lock-in amplifier at each frequency detects the magnitude and phase of the luminosity's response. Corrections for all coordinates are applied by the same DC correctors used previously, but with only one adjustment per cycle for a nine-fold increase in speed. The commissioning of this system uncovered a sinusoidal vibration of the support for the IP that caused relative motion of the two beams and masked the *y* dither. Correcting this gave an immediate luminosity gain, and allowed for successful feedback commissioning.

INTRODUCTION

The PEP-II *B* Factory at the Stanford Linear Accelerator Center collides 9-GeV electrons in the high-energy ring (HER) with 3.1-GeV positrons in the low-energy ring (LER) in order to produce $B\overline{B}$ meson pairs and measure differences in their decay rates due to *CP* violation. Collisions began in 1999, and the machine has operated with currents of up to 3.0 A in LER and 1.9 A in HER, and with a maximum luminosity of 1.2×10^{34} cm^{-2}s^{-1}.

Original Luminosity Feedback

Maintaining the beams of a two-ring collider in head-on collision requires an active feedback that moves one beam relative to the other to seek maximum luminosity. Adjustment is needed in the *x* and *y* (horizontal and vertical) directions. The vertical angle *y′* is also sensitive due to the small aspect ratio (*y*/*x*) of the beams at the IP.

Early on, PEP-II adopted a stepping scheme (previously used in the SLC) that cycles sequentially through the three coordinates. For each, the luminosity is measured four times, with displacements of 0, +*d*, 0, and –*d*, where *d* is a dither made by a closed IP position or angle bump in the HER. The electrons are then moved to the optimum within this range, based on a parabolic fit to the luminosity.

To avoid divergence, motion beyond the step size is not allowed. This size is adjusted automatically as the two beam currents increase, tracking the reduction in IP spot size due to dynamic beta from the beam-beam interaction.

This "slow dither" feedback is in routine use. However, its speed is limited to 750 ms/step by the inductance of the eight iron-dominated corrector magnets that bump the HER at the IP, by the slow Bitbus communication with their power supplies, and by field penetration into the copper vacuum chambers. With four steps each for *x*, *y*, and *y′*, a full cycle takes 9 s. Tuning for luminosity—by, for example, steering, adjusting skew quadrupoles, or bumping the beam in sextupoles—can shift the beam at the IP, lowering luminosity until the feedback makes corrections. Its slow speed thus hinders efficient tuning.

A FASTER DITHER FEEDBACK

Concept

In 2006 we began work on a faster method, which both detects and corrects all three coordinates simultaneously, so that only one corrector change is needed per cycle [1]. Time for measurement and for corrector changes leads to a cycle time of 1 s, a nine-fold improvement.

The electrons are driven sinusoidally in each coordinate. Taking *x* as an example, the variation of luminosity with position, relative to the positrons, of the electron beam at the IP is:

$$L(x) = L_0 \exp\left(-\frac{x^2}{2\Sigma_x^2}\right) \quad (1)$$

where
$$x = x_0 + \tilde{x}\cos\omega_x t \quad (2)$$
and
$$\Sigma_x^2 = \sigma_{x+}^{*\,2} + \sigma_{x-}^{*\,2} \quad (3)$$

is the overlapped *x* beam size at the IP. Expanding for small offset x_0 and dither amplitude $\tilde{x}$, we get:

$$L(x) = L_0\left(1 - \frac{x_0\tilde{x}}{\Sigma_x^2}\cos\omega_x t - \frac{\tilde{x}^2}{2\Sigma_x^2}\cos^2\omega_x t\right)\exp\left(-\frac{x_0^2}{2\Sigma_x^2}\right) \quad (4)$$

When the electrons are centered, the luminosity drops on either side of the peak, giving modulation at $2\omega_x$. Off center, there is additional modulation at the fundamental, and the phase of the luminosity relative to the drive identifies the sign of the offset.

A lock-in amplifier determines the luminosity component at the drive frequency. Beam offsets in all three coordinates can be measured simultaneously by using three frequencies, one per coordinate, and three lock-ins. Then position corrections can be made with a single combined change of all the correctors in the IP bumps.

These magnets have too much inductance to drive the sinusoidal motion. Instead, horizontal and vertical pairs of

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Helmholtz air-core coils were added at four locations surrounding the IP, on vacuum chambers with thin stainless-steel walls to allow for rapid field penetration. These coils do not maintain the beam position, but only drive the oscillation, and so do not need large currents. The usual DC correctors still position the beams for head-on collision, but they are adjusted only once per cycle.

Implementation

Our lock-in amplifiers (Stanford Research Systems model SR830) include a digital frequency synthesizer providing both a locking reference and a sine-wave source for exciting the HER. Each lock-in digitizes the luminosity signal, numerically mixing it with the reference and then low-pass filtering to find the in-phase and out-of-phase luminosity components (which we call the real and imaginary parts) at this frequency. This phase can be shifted by an arbitrary offset to rotate the detected response vector to the real axis, with a positive voltage for a positive offset, giving an output, from (4), of

$$V_x = C_L L_0 \frac{x_0 \tilde{x}}{\sqrt{2}\Sigma_x^2} \exp\left(-\frac{x_0^2}{2\Sigma_x^2}\right) \qquad (5)$$

for the x lock-in, where C_L is the output conversion of the luminosity monitor. V_x is proportional to the offset x_0 and goes to zero when the luminosity is maximized.

The choice of drive frequencies is tightly constrained. To get 1-s cycles, we use a low-pass-filter time constant of 100 ms; consequently, the frequencies must be well above 10 Hz. To avoid interference from the 60-Hz power line, the dithers run above 70 Hz. The upper end is limited by field penetration into the vacuum chambers and by the ±20-V range of our power supplies, which must drive the inductance of the Helmholtz coils. The highest frequency should also be below the second harmonic of the lowest, to avoid crosstalk from the second-harmonic contribution to luminosity. Other power harmonics at 90 and 120 Hz, as well as 5-Hz harmonics from injection, also must be avoided. We now use 93, 77, and 127 Hz for x, y, and y'.

For all three coordinates, we used the HER model to compute coefficients for beam bumps, per µm (or µrad) of bump, for the eight air-core coil pairs. The 1.5-T solenoid inside the *BaBar* detector at the IP couples the x and y planes, and because the bump magnets are inside the series of skew quadrupoles used in decoupling, each bump uses all eight Helmholtz coils.

The computer converts 3 bump amplitudes into 24 DAC voltages proportional to the current needed at each frequency in each of the 8 coils. Using these voltages, a control chassis regulates and combines 3 fixed-amplitude sines from the lock-ins to drive the 8 voltage-controlled current sources (Kepco BOP 20-20M) powering the coils.

At 127 Hz, field penetration lags by up to 13°, differing for the circular chambers and the two directions in the elliptical ones. The control chassis compensates with phase delays equalizing the lag at all coils for each dither.

A computer-controlled feedback loop, run in real-time under RMX III, determines the correction. Our simple algorithm for initial tests always took a fixed-size step in the direction opposite to the sign of the lock-in signal V_x. Our more elaborate approach is based on Newton's method for finding the zero of V_x, dividing it by its slope

$$\frac{dV_x}{dx_0} = C_L L_0 \frac{\tilde{x}}{\sqrt{2}\Sigma_x^2}\left(1-\frac{x_0^2}{\Sigma_x^2}\right)\exp\left(-\frac{x_0^2}{2\Sigma_x^2}\right) \approx C_L L_0 \frac{\tilde{x}}{\sqrt{2}\Sigma_x^2} \qquad (6)$$

A new slope is measured with every move, but for stability the algorithm uses a running average excluding tiny moves and negative slopes (when $|x_0| > \Sigma_x$ in (6)). The average slope is then near its peak and gives an estimate of Σ_x. To avoid overshoot, we apply less than 100% of the computed correction and limit the maximum step.

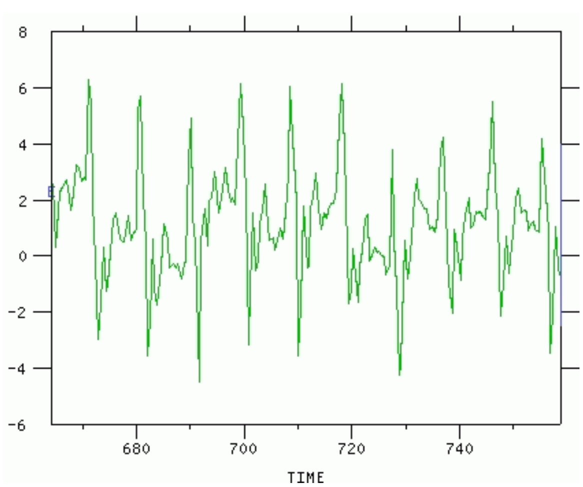

Figure 1. Real axis of the y lock-in, monitoring vertical dithers taken every 9 s by the old feedback, which stepped up then down by 0.4 µm.

COMMISSIONING TESTS

Verifying the Beam Bumps

Initial tests of the Helmholtz-coil bumps drove the Kepco supplies directly with DC from the DACs. Each bump amplitude was increased until the luminosity dropped, and bump closure could be observed with PEP beam-position monitors. Then the corresponding DC corrector bump was used to restore the luminosity, allowing a calibration of the IP position or angle offset, and testing the orthogonality of the three bumps.

Detecting Beam Position

For each dither coordinate, we excited the Helmholtz coils and monitored the lock-in signal to test its ability to detect the steps taken by the slow-dither feedback during its sequence of beam movements. The lock-in's phase offset was adjusted to align a positive beam displacement with the positive real axis (Fig. 1).

Vibration inside the Detector

We next halted the slow dither and let the new feedback control the beam. Surprisingly, it had little vertical control. The detected y position oscillated every few seconds, as did the corrections, suggesting an unstable feedback despite a low gain. But when a higher minimum move cut off the corrections, the detected position still oscillated.

The spectrum of the luminosity was complex (Fig. 2a). The expected lines at the three dithers, and at the 60-Hz power line, all had sidebands ±9.7 Hz away. A similarly high line appeared at 9.7 Hz itself. This low frequency suggested mechanical motion, as did Fourier transforms of beam position measurements. We had observed luminosity drops of 2 to 3% when the three fast dithers start while the slow dither is running. Could there be a similar impact on luminosity from the 9.7-Hz line?

The source was traced to a vertical vibration of the "support tube," a 10-m-long, 0.4-m-wide, stainless-steel and carbon-fiber tube running through *BABAR* and carrying the beampipe, strong permanent-magnet bends and quadrupoles, and the silicon vertex tracker at the IP. A comparison of the luminosity modulation to the slow feedback's dither steps indicated a relative beam motion of 1 µm at the IP, compared to a 5-µm vertical focus.

To measure the impact of this vibration and as a quick compensation, we turned on the vertical fast-dither drive at 9.75 Hz with a 1-µm amplitude. This pushed the electrons relative to the positrons in a beat that alternately increased and decreased their separation. The peak luminosity gained an immediate 4%. The operators began tuning the drive frequency in an attempt to hold the peak. A vertical brace was then devised for the forward end of the support tube (since the center is inaccessible), reducing the relative motion of the beams by a factor of 5.

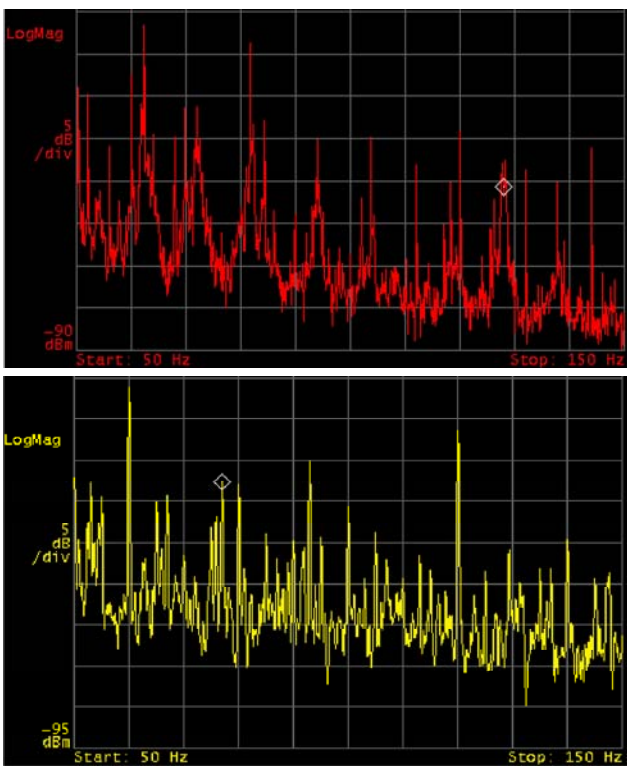

Figure 2. Spectrum of luminosity from 50 to 150 Hz with fast dither on: (a) with support-tube vibration, showing prominent sidebands at ±9.7 Hz around dither frequencies (94, 72, and 128) and 60 Hz, and (b) after installing support-tube brace, eliminating sidebands around dither frequencies (93, 77, and 127) and 60 Hz.

Testing in Feedback Mode

With the vibration suppressed, feedback testing was resumed. The spectrum was cleaner (Fig 2b). The vertical position no longer oscillated, and the feedback kept the beam stable for long test runs, both at steady currents and during fills, allowing careful tuning of loop parameters.

The tests also allowed us to improve the software, which operates within a general feedback architecture dating to the SLC program in the 1990s. The software can alternate between slow and fast dither, with the start of one automatically halting the other. It decreases the fast-dither amplitudes as the rings fill. The averaged slope is initialized using (6) and an estimate of the Σ beam size.

Dithering in all three coordinates simultaneously sacrifices the highest peak luminosity for faster corrections. This is valuable for tuning and filling. For steady integration with little tuning, we supplemented the fast "tweak mode" with a new "peak mode," using dithers reduced by a factor of 3. To compensate, the lock-in time constants increase from 0.1 to 1 s, and the loop is slowed to 3 s. This rate is still 3 times faster than the old feedback while providing more integrated luminosity (Fig. 3).

CONCLUSION

Fast-dither feedback simultaneously adjusts the x and y position, and the y' angle, of the electrons at the IP of PEP-II, optimizing collisions with the positrons. Its 1-s cycle is nine times faster than the sequential slow-dither feedback it replaces, allowing for rapid tuning and better tracking during fills. A second mode with smaller dithers and a 3-s cycle gives better integration than the old feedback while still responding more quickly to perturbations.

REFERENCES

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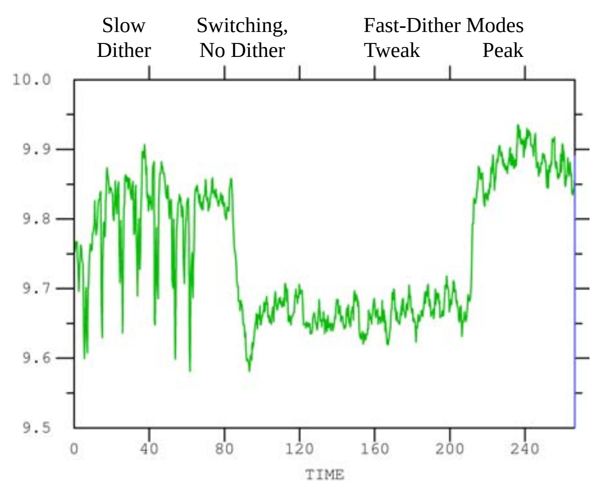

Figure 3. Luminosity at steady currents, comparing slow-dither feedback to fast dither in tweak, then peak, modes.