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Tune Feedback in PEP-II*

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Abstract

The PEP-II B Factory is a 2.2-km-circumference, storage-ring collider in which 9-GeV electrons in the high-energy ring collide with 3.1-GeV positrons in the low-energy ring. In 2002 we installed tracking loops to measure each ring's horizontal and vertical tunes. (The tune, a critical parameter for beam stability and for luminosity, is the fractional part of the number of oscillations of the beam about the central orbit in one revolution.) Each tracker uses a lock-in amplifier to measure the phase difference between a sinusoidal excitation of the beam and its response. If the drive frequency is swept across the tune resonance, this phase drops by 180 degrees. The tracker continually adjusts the frequency to maintain the phase at the middle of this transition. This drive frequency, normalized to the revolution frequency, gives the fractional tune. Recently these four loops (electron and positron, *x* and *y*) have been extended to controlling the tunes, by adjusting combinations of quadrupole magnets. However, at the same time we have increased the luminosity by setting the tunes just above the half-integer resonance, where a misadjustment can quickly lose the beam, and beam-beam forces from collisions make the tune spectra broad and complex. Consequently, we added a few non-colliding bunches to the fill pattern of each ring. Fast gates let us excite and measure only these bunches, and let us stop feedback damping of transverse motion for them.

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I.

I. INTRODUCTION

THE PEP-II B Factory, a 2.2-km asymmetric collider at the Stanford Linear Accelerator Center studies *CP* violation by tracking decays of B and $\overline{B}$ mesons moving in the lab frame. At a single interaction point, 9-GeV electrons in the high-energy ring (HER) collide at zero crossing angle with 3.1-GeV positrons in the low-energy ring (LER). Collisions were first observed in July 1998, during commissioning without the *BABAR* detector, which was installed in May 1999. By the time of this conference, luminosity has reached a peak of $6.5\times10^{33}\ \mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}$, doubling the design goal of 3.0. We routinely collide 1.7 A of positrons with 1.1 A of electrons.

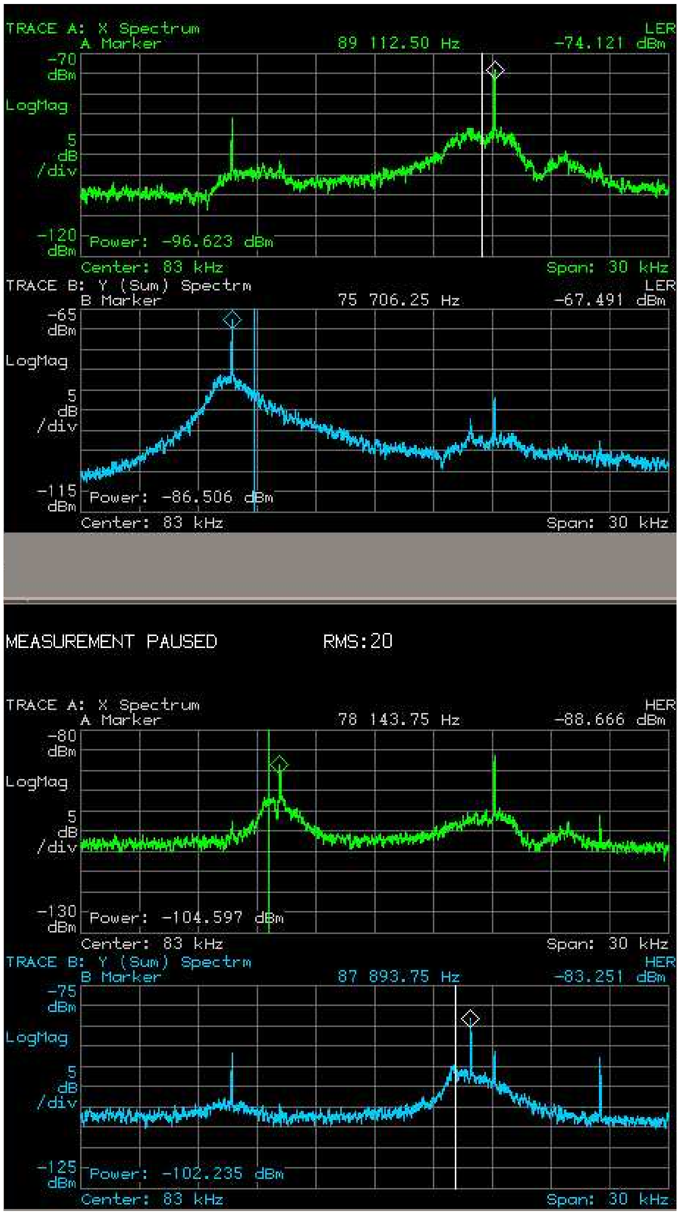

Figure 1. Spectrum of colliding beams from 68 to 98 kHz, after mixing down from 952 MHz. From top to bottom, LER *x*, *y*; HER *x*, *y*. The revolution frequency is 136.3 kHz. The vertical bars are references indicating the nominal tunes, while the spikes on the traces indicated by the diamond markers are the excitation frequencies of the tune trackers.

The horizontal and vertical (betatron) tunes ν_x and ν_y—the number of *x* or *y* oscillations about the central orbit per trip around the ring, due to focusing by the quadrupole magnets—are essential parameters in determining beam stability. In general, each tune must not be an integer or low-order rational number, since an orbit that precisely repeats after a few turns will grow in amplitude, leading to beam loss. An off-axis particle encountering a beam of opposite charge centered on the axis gets an additional focusing kick and so a positive tune shift. PEP's high luminosities involve high beam-beam forces, with correspondingly large tune shifts, creating a smear of tunes rather than a single working point in *xy* tune space and so making it harder to avoid losing particles on rational linear combinations of the *x* and *y* tunes (and other resonant combinations involving the synchrotron tune, which describes longitudinal oscillations in energy and round-trip time). Consequently, careful attention must be paid to measuring and controlling the betatron tunes.

In our standard tune measurement [1], four 15-mm-diameter "button" electrodes flush with the wall of the vacuum chamber pick up signals from the passage of the beam. Because they are placed at 45° to the *x* and *y* axes, we use broadband 180° RF hybrids to form horizontal and vertical offset signals (e.g., for vertical, we use the sum of the top buttons minus the sum of the bottom ones). These signals are mixed at 952 MHz, twice the ring's RF frequency, bringing them down to baseband for display on the fast-Fourier-transform spectrum analyzers of Fig. 1.

Horizontal and vertical bunch-by-bunch transverse feedback provides strong damping for beam motion, applying a correction kick to each bunch as it passes through *x* and *y* pairs of stripline kickers. To obtain sufficient signal to measure tunes, we sum a random-noise excitation signal with each feedback signal at the input to its preamplifier. This allows the tune system to share the expensive amplifiers and avoids presenting the beam with additional impedance from extra kickers.

II. TUNE TRACKING

PEP operators carefully control the betatron tunes to maintaining high luminosity, using suitable linear combinations of the tune-adjustment quadrupoles (the "tune multiknobs") to line up the *x* or *y* spectra against reference markers. A feedforward loop [2] also adjusts these multiknobs to compensate for tune variation with current as the rings are filled and the currents decay. The operators frequently consult

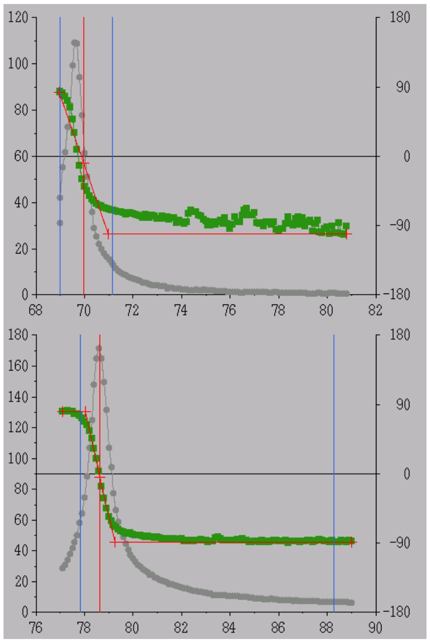

Fig. 2. Frequency scans (kHz) of the LER *x* (above) and *y* (below) tune trackers, showing the amplitude (gray, left scale in μV) and the phase (green, right scale in degrees). The *x* tune is just above the half integer (68.15 kHz), but there were no electrons colliding with these positrons, and so the resonances have sharp peaks and monotonic 180° phase transitions.

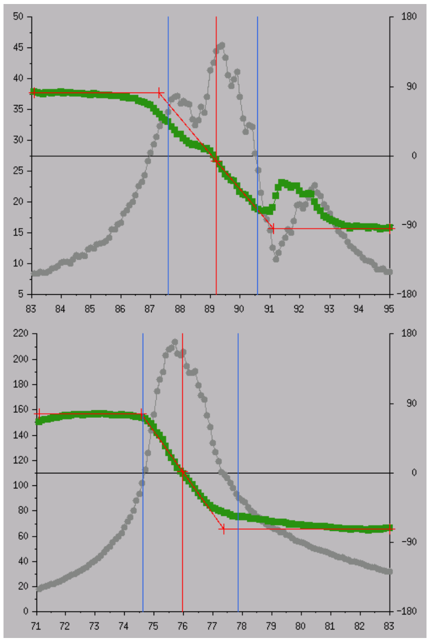

Fig. 3. Same as Fig. 2, but the beam is in collision, with the horizontal tunes of both rings away from the half integer. The collisions broaden the peaks and slow the phase transition. The *x* tune has multiple peaks and the phase transition is no longer monotonic.

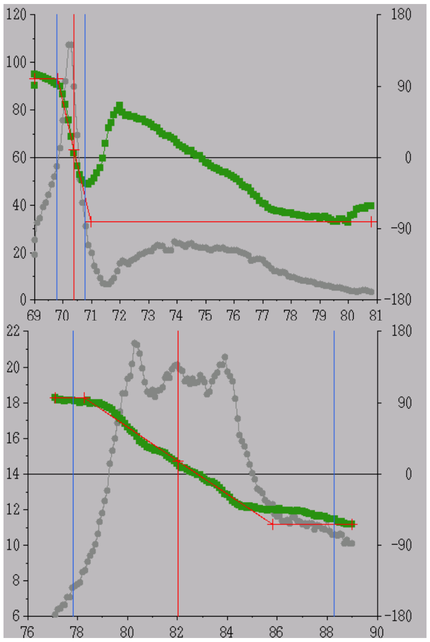

Fig. 4. Scanned with settings of Fig. 2, but after the HER was filled and collisions resumed. Both beams have x tunes just above the half integer. Compared to Fig. 3, the peaks are broader, the *y* tune has multiple peaks, and the amplitude of the *x* tune has a long plateau. The *x* phase transition is strongly non-monotonic.

a history plot of the knob moves to restore a previously successful configuration.

In collision, the spectral peaks are lower and broader, often with multiple peaks and a plateau toward higher frequencies. This makes it difficult to characterize each tune with a single number, and to reproduce a previous operating state. Fig. 1 shows typical traces in collision, away from the half-integer resonance.

As a result, we supplemented our spectrum analyzer with a "tune tracker," which measures the beam's response to sinusoidal excitation at the center of the tune resonance, and follows changes in that frequency by monitoring the phase, not the amplitude, of the response [1]. The input is the same downconverted signal seen on the spectrum analyzers of Fig. 1.

When a sinusoidal excitation driving a resonant system is swept in frequency across the peak, the phase of the response drops by 180° relative to the drive. The linear slope at the center of the phase transition allows for a simple tracking loop: the tune tracker avoids the difficulties of following an amplitude peak by driving at one frequency that is constantly adjusted to maintain the phase at the center of this transition. This drive frequency, normalized to the 136.3-kHz revolution frequency, is the fractional tune. A digital lock-in amplifier (Stanford Research Systems 830), which includes a sine source, makes a quadrature measurement of the response at the drive frequency, and so obtains both amplitude and phase. A computer then reads the phase via GPIB and adjusts the frequency, using a measured slope of the phase-frequency curve obtained from an initial scan such as that shown in Fig 2.

III. TUNE FEEDBACK

The tracker provides an automatic method of characterizing each tune with a single number, and so is naturally extended to closing the loop by controlling the tune with feedback, using the quadrupole-magnet multiknobs normally used for manual adjustment. The flowchart of Fig. 5 has both the tracking loop to measure the tune, and, after averaging, the tune-feedback loop to adjust the magnets.

Note that the multiknob for manual adjustment must now be changed so that the feedback does not undo any intentional operator adjustment. When feedback is on, the operator's multiknob now includes an additional command to move the feedback setpoint to match the magnet change.

A preliminary version of this code was briefly tested for five hours in June 2002, as shown in Fig. 6. Up to three of the four tunes (HER and LER, *x* and *y*) were controlled as we varied loop gains. The feedback compensated for operator adjustments that normally would unintentionally affect tune, such as changes to skew quadrupoles.

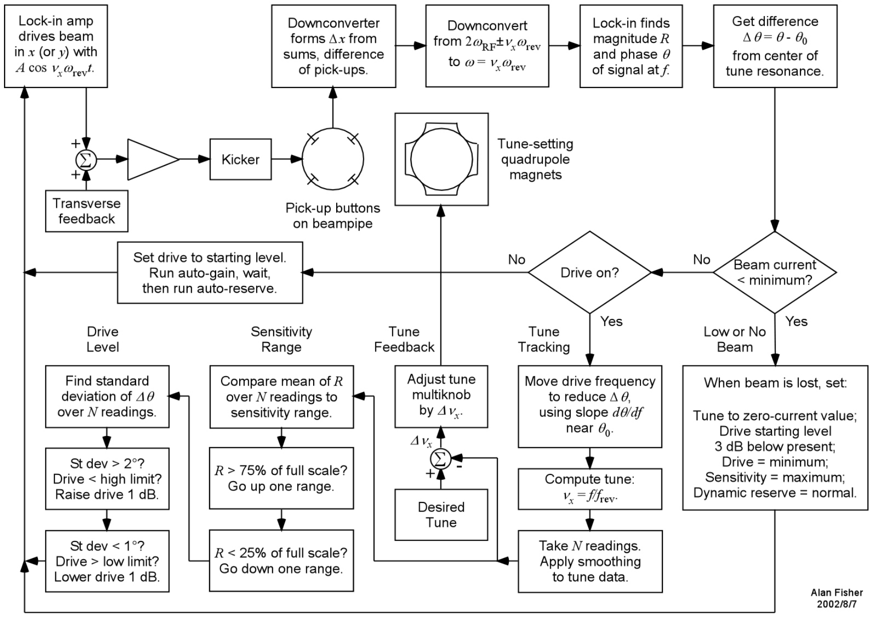

Fig. 5. Flowchart showing the tune tracking loop. The slower tune feedback loop then averages several measurements before adjusting the quadrupoles.

IV. PILOT BUNCHES

During the first half of 2003, we moved our working point for better luminosity, bringing the horizontal tunes in both rings to values just above the half integer. The peaks on the horizontal spectrum got much broader, with a long plateau extending to higher frequencies, as shown in Fig. 4. The broad and distorted peaks of colliding bunches can now be difficult even for the tune tracker, since the phase curves for the x tunes are no longer monotonic. Also, the spread makes it difficult to use the value of the tracker as a reference to reproduce a good collision setup from an earlier day, since the tracker follows the midpoint of the resonance, but the midpoint moves as the luminosity is raised.

To continue tracking despite this wide tune spread, we introduced a few noncolliding bunches, known (following CERN) as "pilot" bunches. These pilots make a better input for tracking. They also provide a better reference for recovering a previous high-luminosity operating condition. High luminosity moves the center of the resonance to high frequencies, but the low-frequency end of the peak remains anchored at the tune of noncolliding bunches. Therefore, while making adjustments to restore luminosity, it is less suitable to try to keep the middle of the resonance constant than to hold the tunes of the pilot bunches steady.

We typically add four pilot bunches to the end of the fill pattern, which now has approximately 1100 bunches with a spacing of 6.3 ns, and a gap of 200 ns, which provides a rise time for the field of the abort kicker so that all bunches get cleanly sent to the dump during an abort. To extract the signal from 4 of 1100 bunches, we use a GaAs RF switch with a 2-ns rise time. For low leakage, we use two switches in series, giving about 40 dB of suppression.

The bunch signals pass through components with 3-GHz bandwidths up to the switches, which then can easily separate the bunches in the time domain, directing them into two streams. The colliding bunch signals go, as before, to the spectrum analyzers. The pilot signals pass through a different set of mixers to the tune trackers, which are reassigned to monitor the pilots rather than the whole train. An additional spectrum analyzer is also available for the pilots.

Despite the gating, the pilot signals are still hard to locate among the other bunches without further effort. We inserted an additional fast switch for each tune to limit the tracker's sinusoidal excitation to the pilot bunches. Then, because the bunch-by-bunch transverse feedback system damps the beam's response to this shaking, we also used the switch to toggle the feedback off as the shaking is turned on.

The result is a strong tune transition, even sharper than that of Fig. 2, which has feedback damping. Tests of tune feedback with this arrangement have shown that it can be stable over a period of hours, as shown in Fig. 7.

V. VANISHING PILOTS

The pilot bunches have the lowest tunes in the beam. When operating just above a tune of 0.5, the pilots are the bunches closest to the resonance. If these are safe, then the colliding bunches are safe too, but the pilots can be lost by a small tune adjustment. Since they do not contribute to luminosity, the adjustment could produce higher luminosity even as it loses the pilots. Their disappearance, of course, makes them useless for feedback and has in fact been a constant problem, limiting the usefulness of the technique and even the duration of the tests.

To avoid feeding back on noise, the software now looks first at the bunch-current monitor. Before executing a feedback correction, both the total charge in the pilots and the magnitude of the tracker's signal must exceed threshold values. If the pilots are empty, then the feedback is replaced by the older feedforward loop until the pilots are refilled at the next top off.

Additionally, we have experimented with colliding pilots. This seems a contradictory concept, but the intent is to have a small tune shift, just enough keep the pilots in the machine, but not enough to make a significant change in their tunes. At the present time, seven half-full colliding bunches appear to remain in the ring and may provide the path we need to a useful feedback.

VI. ACKNOWLEDGMENT

We thank the PEP operators and physicists for their support and patience through many rounds of testing.

VII. REFERENCES

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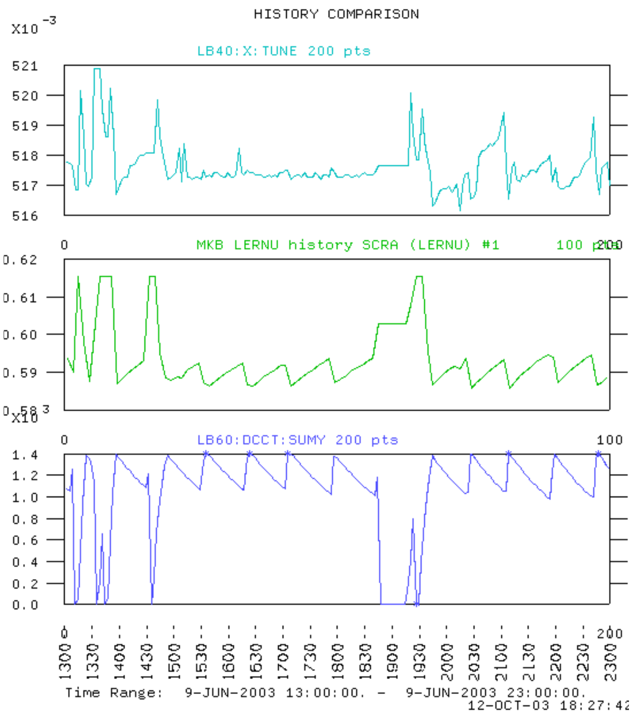

Fig. 7. Feedback tested for 3.5 hours on LER *x* tune (top) using pilot bunches. Tune variations seen before and after the test are flattened out by feedback, except for intentional perturbations introduced for testing. The flattening requires only subtle changes in the tune magnet multiknob (center). The LER current is shown at bottom