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Alan S. Fisher *et al.*

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Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

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Upgrades to PEP-II Tune Measurements

Alan S. Fisher, Mark Petree, Uli Wienands, Stephanie Allison, Michael Laznovsky, Michael Seeman,* and Jolene Robin†

Stanford Linear Accelerator Center
2575 Sand Hill Road, Menlo Park, CA 94025, U.S.A.

Abstract. The tune monitors for the two-ring PEP-II collider convert signals from one set of four BPM-type pickup buttons per ring into horizontal and vertical differences, which are then downconverted from 952 MHz (twice the RF) to baseband. Two-channel 10-MHz FFT spectrum analyzers show spectra in X-window displays in the Control Room, to assist PEP operators. When operating with the original system near the beam-beam limit, collisions broadened and flattened the tune peaks, often bringing them near the noise floor. We recently installed new downconverters that increase the signal-to-noise ratio by about 5 dB. In addition, we went from one to two sets of pickups per ring, near focusing and defocusing quadrupoles, so that signals for both planes originate at locations with large amplitudes. We also have just installed a tune tracker, based on a digital lock-in amplifier (one per tune plane) that is controlled by an EPICS software feedback loop. The tracker monitors the phase of the beam's response to a sinusoidal excitation, and adjusts the drive frequency to track the middle of the 180-degree phase transition across the tune resonance. We plan next to test an outer loop controlling the tune quadrupoles based on this tune measurement.

INTRODUCTION

The PEP-II *B* Factory, a 2.2-km asymmetric collider at the Stanford Linear Accelerator Center [1], was built in collaboration with the Lawrence Berkeley [2] and Lawrence Livermore [3] National Laboratories to study *CP* violation by tracking decays of *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 Workshop, peak luminosity has reached 4.6×10^{33} $cm^{-2}\cdot s^{-1}$, exceeding the design goal of 3.0×10^{33}, and we collide up to 1750 mA of positrons on 1050 mA of electrons.

These high luminosities require high beam-beam tune shifts. In operating the rings, and especially in filling them while colliding, careful attention must be paid to controlling the betatron tunes. However, these conditions also make tune peaks hard to observe. Out of collision, the spectrum analyzer shows tall, narrow peaks at the betatron tunes, but in collision the beam-beam tune spread lowers and broadens the peaks, leaving them at times barely above the noise floor.

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* Present address: Massachusetts Institute of Technology, Cambridge, Massachusetts.
† Present address: University of New Orleans, New Orleans, Louisiana.

Two complementary improvements have been pursued. New downconverters for the tune signals have been built on the same principle as the original ones, but with changes to improve the signal-to-noise ratio. In addition, a tune tracker has been built using a digital lock-in amplifier for each of the four tune planes (HER and LER, *x* and *y*). The tracker measures the beam's response, via the same downconverter, to sinusoidal excitation at the center of the tune resonance, and follows changes in that frequency by monitoring the phase, rather than the amplitude, of the response.

IMPROVED DOWNCONVERTER

The original tune monitors (one per ring) were described at the 1998 Beam Instrumentation Workshop [5]. They provided strong signals during single-ring commissioning and through the first years of collisions, even with bunch-by-bunch transverse feedback damping betatron motion. However, with increasing luminosity it has become more difficult to see the betatron tunes while in collision, because the beam-beam tune shifts broaden and flatten the peaks, at times bringing them down to the noise floor. An additional concern is that tight budgets during construction left us without a complete spare chassis for quick substitution when occasionally an amplifier, mixer, or power supply fails. To address both of these issues, we recently made a new chassis (Fig. 1) for each ring, with several modifications, rather than making a simple duplicate as a spare. The goal was a 5-dB improvement in the signal-to-noise ratio. The old units have now become the spares.

One might first ask why a downconverter is needed. Our digital spectrum analyzers compute the spectrum (after the downconverter) from a fast Fourier transform (FFT) over a 10-MHz bandwidth, and normally zoom in on a 30-kHz range within one ring revolution frequency (136 kHz) of 952 MHz, twice the ring's RF frequency. If instead we used a broadband spectrum analyzer, it would include downconversion and could

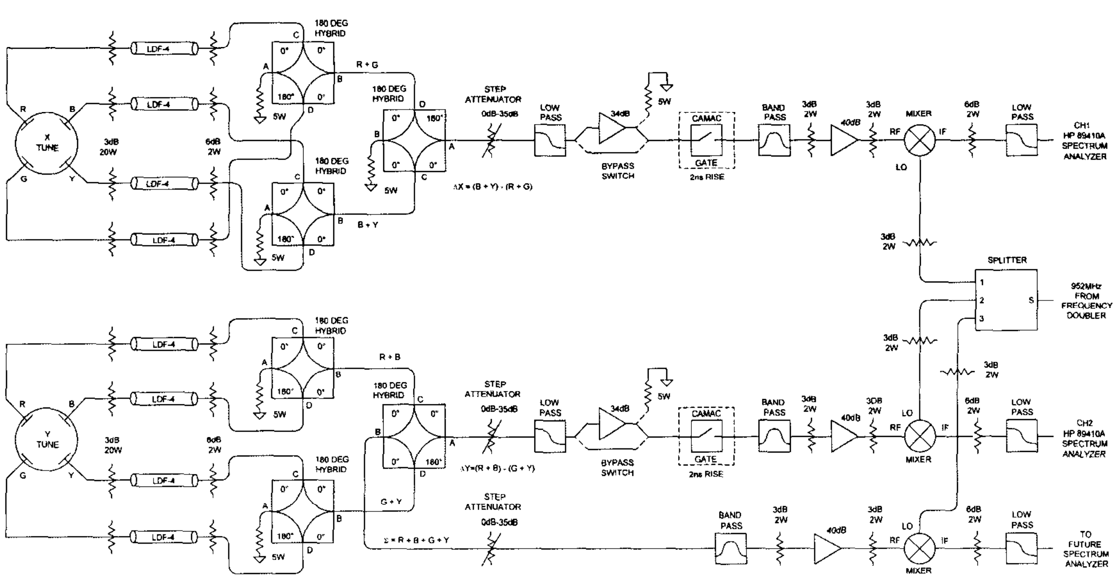


FIGURE 1. The new PEP-II tune monitor, showing the pick-up buttons, the downconverter, and the signals going to the spectrum analyzer.

TABLE 1. Beta Functions at Pickups.

Plane	Quadrupole	β (m)
	Original Layout	
LER x	QDP-3014	3.1
LER y	QDP-3014	25.4
HER x	QFP-8062	24.5
HER y	QFP-8062	9.9
	New Layout	
LER x	QFP3-3042	23.1
LER y	QDP-3014	25.4
HER x	QFP-8042	37.3
HER y	QDP-8012	36.9

directly display the tune monitor's frequency range. However, the sensitivity is not as good. We have examined the signal directly from one of our 15-mm-diameter pick-up buttons on two broadband spectrum analyzers (a Rohde and Schwarz FSP series and an Agilent PSA series). Both lose the betatron peaks in the noise floor, even when they are plainly visible with our downconverter.

For greater simplicity and fewer long Heliax cables, the old downconverters formed the Δx and Δy signals from one dedicated set per ring of four pick-up buttons (identical to those used for beam position monitoring). Mechanical stability requirements placed all buttons at beampipe supports adjacent to quadrupoles, giving a choice of either a large β_x and small β_y near a QF, or the opposite at a QD. For the new downconverters, we added a second set of cables to get the highest available betas for both planes, and so more signal. Table 1 shows the improvement in beta functions.

The Heliax cables from the tunnel lead to 180° hybrids that form the Δx and Δy signals. Next an amplifier provides gain for small signals obtained when the charge per bunch is small, a condition typical of commissioning or machine development but not of normal operating currents, which can saturate the amplifier. In the old system, we could avoid saturation by first attenuating the signal with a step attenuator at the amplifier input. In terms of gain, this is an adequate solution, but at high luminosity we needed to avoid the additional noise introduced the attenuator as well as the amplifier. Instead, in the new design an RF switch bypasses the amplifier. In addition, the new amplifier offers a lower noise figure and better power handling, as does the second amplifier before the mixer. The step attenuator moves in eight 5-dB rather than 10-dB steps, since we'd prefer smaller steps to the larger range. We also selected a mixer with higher conversion efficiency.

Other changes were made for modularity and ease of repair. The main power supply was moved out of the chassis to a separate rack-mounted unit. It provides the input for individual regulators next to each amplifier and frequency doubler (providing the 952-MHz reference). We replaced the single doubler of the old system with one per ring, plus an option to share one if the other fails. The output splits three ways, to provide a local oscillator for mixers for the x, y, and 4-button-sum channels.

There is a phase shifter on the 476-MHz input to each doubler, because the beam's frequency components symmetrically above and below 952 MHz combine with the reference in the mixer in a phase-sensitive manner, with the output going from zero to

TABLE 2. Design Calculations for Small and Large Input Signals.

System	Attenuator (dB)	Amplifier Bypassed?	Gain (dB)	Noise Figure (dB)	Signal to Noise (dB)
Old	0	No	6.7	26.2	37.4
New	0	No	19.1	24.5	40.7
Old	30	No	-22.8	55.7	27.9
New	0	Yes	-8.9	30.9	45.9

a maximum as the 952 phase shifts by 90°. Because the x channel has a different path from the buttons to the mixer, compared to the y and sum channels, the cable length for the reference to the x mixer is adjusted to peak at the same phase as y.

The signal to noise for the four tunes shows improvements of the anticipated magnitude (Fig. 2), although it is puzzling that the biggest improvements were not in the planes with the biggest increases in beta. The figure also shows that the improvement for LER is larger than for HER, probably because LER typically collides with 1.5 to 1.7 times more charge per bunch, and so used a larger step attenuator setting than HER (30 rather than 20 dB) with the old system; it thus benefited more from bypassing the amplifier. Some improvement also came from having the two independent phase shifters, making it easier to peak up all four signals. However, these comparisons were not systematic, because the change-over was made during colliding-beam operation, moving cables during brief intervals without beam. The traces thus show similar, but not identical, machine conditions.

TUNE TRACKER

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 [6] also adjusts these multiknobs to compensate for tune variation with current as the rings are filled and the currents decay. The operators frequently consult a history plot of the knob moves to restore a previously successful configuration.

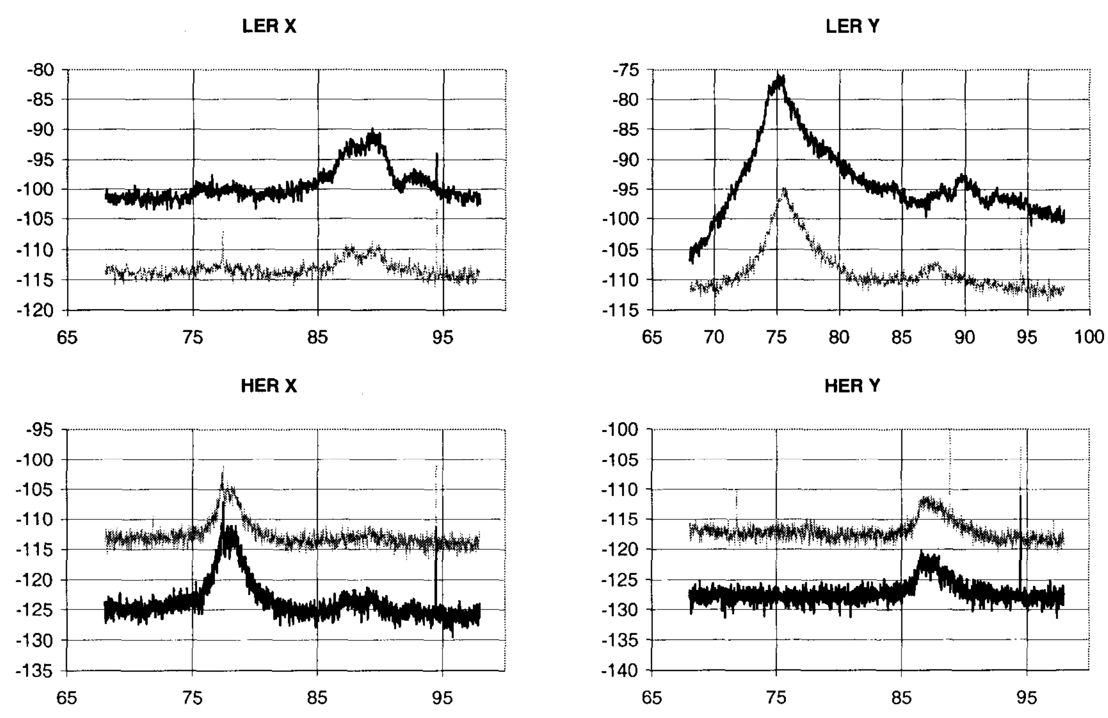


FIGURE 2. Spectra showing typical improvements when the old downconverters (light gray trace) was replaced by the new (heavy black). Amplitude in dBm vs. frequency in kHz.

More complete information would be helpful. These spectra are complex and gradually change shape as the currents decay and the beam-beam forces change. The quadrupoles, the currents, and the beam-beam forces all affect the tunes, but the multiknob history includes only the quadrupole changes made by the operators and by the feedforward, mostly as compensation for the evolution of the beam-beam forces. It would be desirable to plot the history of a single tune value characterizing all the changes affecting the beam, but it is hard to pick out a single number from the amplitude of a broad spectrum. We have tried an algorithm that searches every few minutes for a designated spectral peak, recording its frequency and height, but it generally loses track as the peaks evolve.

The phase shift across the tune resonance provides an interesting alternative. The two channels of the spectrum analyzer for each ring are normally set to display only the magnitude of the Δx and Δy power spectra, as we excite the beam with broadband random noise. To see the phase, we put the excitation into channel 1 and either Δx or Δy into channel 2. The instrument can then plot the magnitude and phase of the transfer function, the ratio of channels 2 to 1. The magnitude is just the familiar power spectrum, since the excitation is uniform. The phase drops by 180° (Fig 3) as the

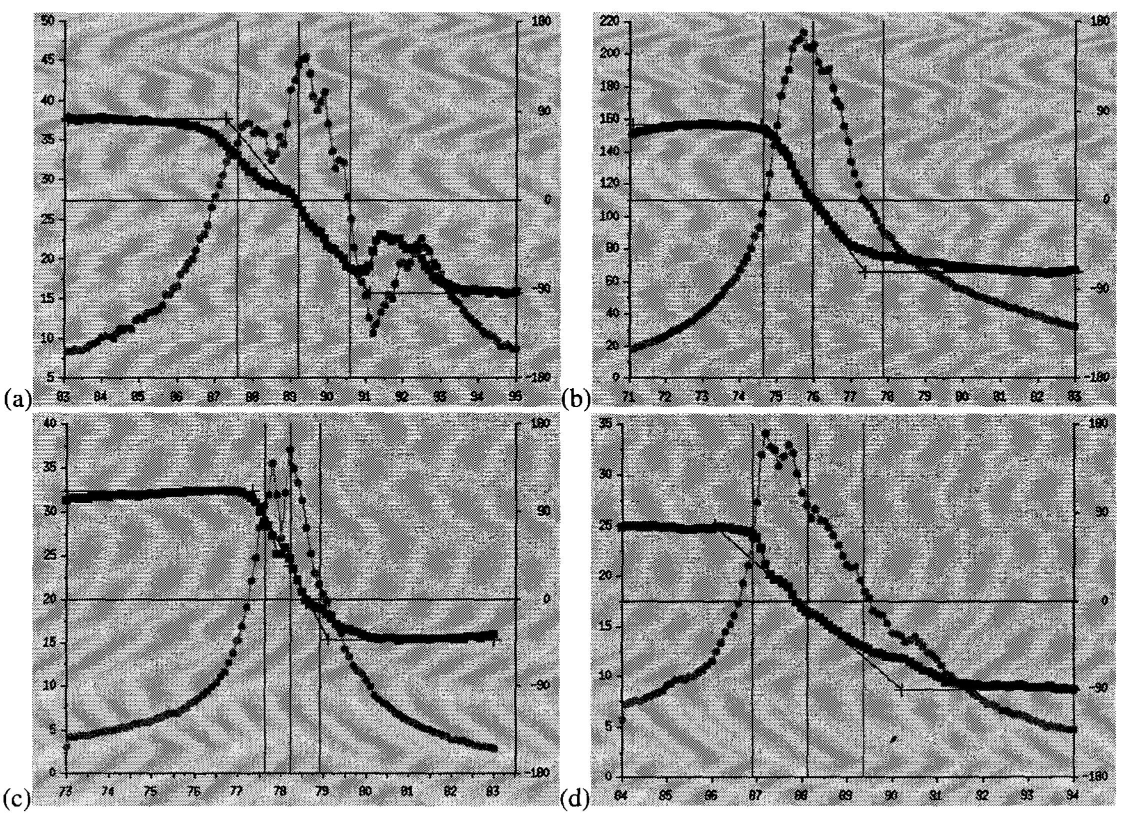


FIGURE 3. Frequency scans of the tune trackers for (a) LER x, (b) LER y, (c) HER x, and (d) HER y, The horizontal scale is in kHz. The vertical scale on the left is the peak's magnitude in μV, while the phase curve uses the scale on the right in degrees. A cross marks the target phase, at the middle of the 180° transition. A slope is computed from a linear fit of points near the target phase, including as many points as possible within the user's cursors without exceeding a chi-squared criterion. Because the beams are colliding, the tunes can have multiple peaks and a non-monotonic phase, as in LER x. Nevertheless, the target phase appears to provide a robust marker to characterize the tune.

frequency crosses the tune resonance. Near the center, the phase can be modeled as a smooth monotonic ramp, making it perfect for a feedback loop tracking the frequency corresponding to this central phase. Also, unlike a peak height, there is little change in this curve with current.

Using the spectrum analyzer, we would have to examine the full trace to extract this frequency. With our two-channel instrument, we would have to forgo separating the beam motion into x and y traces, instead merging both into a single spectrum by using only two diagonally opposite buttons rather than all four.

However, for this purpose we do not need the full spectrum, but only the phase of the response to one frequency at a time. In particular, a digital lock-in amplifier is really a single-frequency equivalent of our spectrum analyzer. Both digitize the incoming signal and translate the desired central frequency down to baseband with the digital equivalent of a quadrature mixer—multiplication by a cosine and sine. The spectrum analyzer then uses a low-pass filter and an FFT to obtain the full spectrum. The lock-in uses a narrow low-pass filter to extract only the DC component, corresponding to the in-phase and quadrature power at the central frequency. Not surprisingly, the resolution is similar, but the lock-in is much less expensive. Also, much less drive power goes into the beam, since we excite only one frequency with a continuous sine, rather than spreading the drive over a band.

Fig. 4 shows the main tune-measuring loop, plus secondary loops to adjust the drive power and keep the instrument in a suitable sensitivity range. The internal sine-wave source of the lock-in amplifier (a Stanford Research Systems SR830) excites the beam by adding its signal to the error signal for transverse feedback (and to the random noise from the source in the spectrum analyzer). The sum goes to the feedback

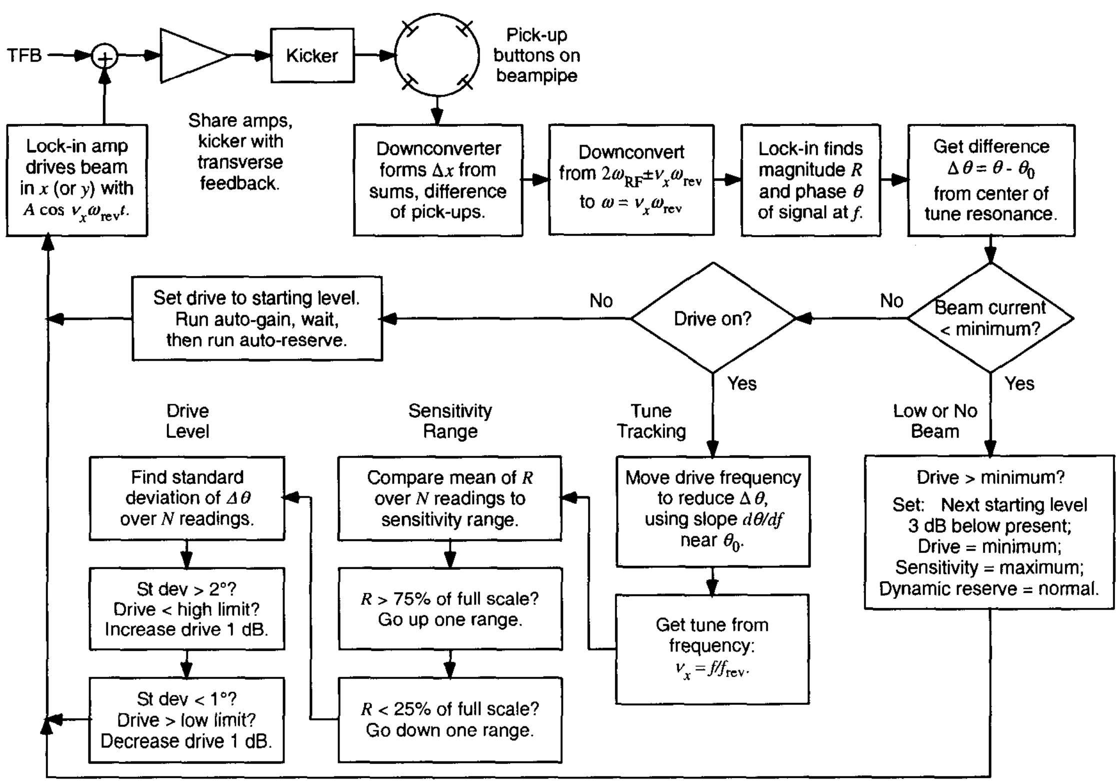


FIGURE 4. Flow chart for the tune tracker.

amplifiers and kicker. The input to the lock-in is the same downconverted beam response given to the spectrum analyzer.

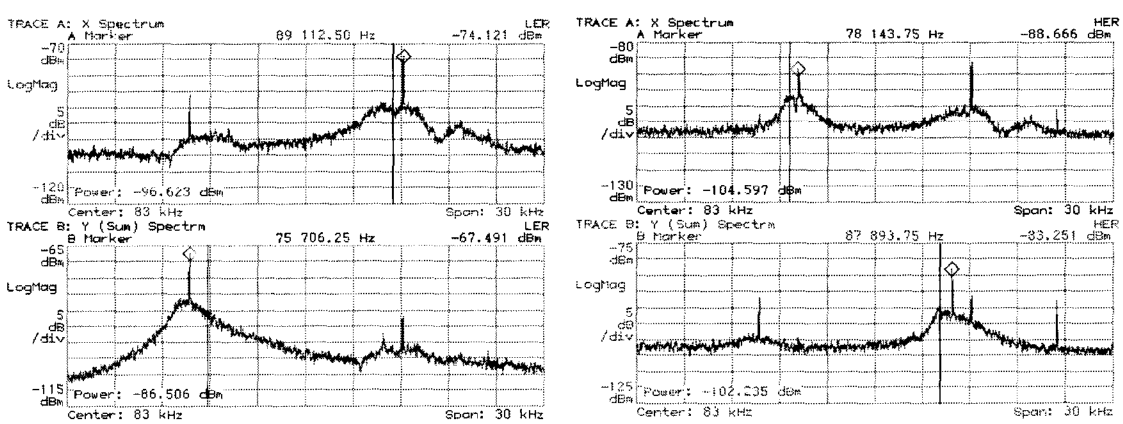
A computer running the EPICS control system communicates with each lock-in through GPIB. To set up the tune tracker, the computer first scans the frequency f across the peak and measures the amplitude and phase of the response (Fig. 3). The phase θ_0 at the middle of the transition becomes the loop's target phase. The slope $d\theta / df$ around this phase is also noted. Then the frequency is set to the middle of the transition to start the loop. Every second the computer reads the phase θ and changes the frequency to correct the phase error:

$$\Delta f = g \frac{\theta - \theta_0}{df / d\theta} \tag{1}$$

where the gain g reduces the step size to avoid overshoot. The frequency gives us the tune. A spike at this frequency from the beam excitation appears on the spectrum, as shown in Fig. 5. The stripchart of Fig. 6 shows the tunes over a 6-hour period, taken from the first 24 hours of tracking in all four planes.

We implemented the tune loop shortly before this Workshop and are now writing code for the drive and sensitivity loops. At present the computer is remote and connects via an Ethernet-to-GPIB interface (Agilent E2050A). It reads all four tunes at 1 Hz. For higher speed or if network traffic eventually becomes a limitation, a local computer with a GPIB card may be used.

We had expected that the effect of the adjustments in the tune multiknobs, by the operators and by the feedforward loop, was to hold the actual tunes constant, with all the knobbing serving to offset tune changes due to currents and beam-beam forces. The stripchart shows that the tunes are not flat between fills, despite these adjustments. With the idea that we might optimize the luminosity by holding the tunes constant, we have begun preparing a true tune feedback that will use the outputs of the tune trackers to slowly adjust the tune multiknobs. To quickly explore this idea in a simpler way, we tried adjusting the tune-versus-current coefficients in the feedforward to flatten the tracker traces. Some flattening may be seen in the last two fills of the stripchart, as yet with little effect on luminosity.



(a) (b)

FIGURE 5. Spectrum analyzer traces for (a) LER and (b) HER with narrow frequency spikes from the tune tracker visible on all four peaks. Due to coupling and collisions, a spike can appear on both planes and both rings. The horizontal range is 68 to 98 kHz; the vertical scale is 5 dB/div.

ACKNOWLEDGMENTS

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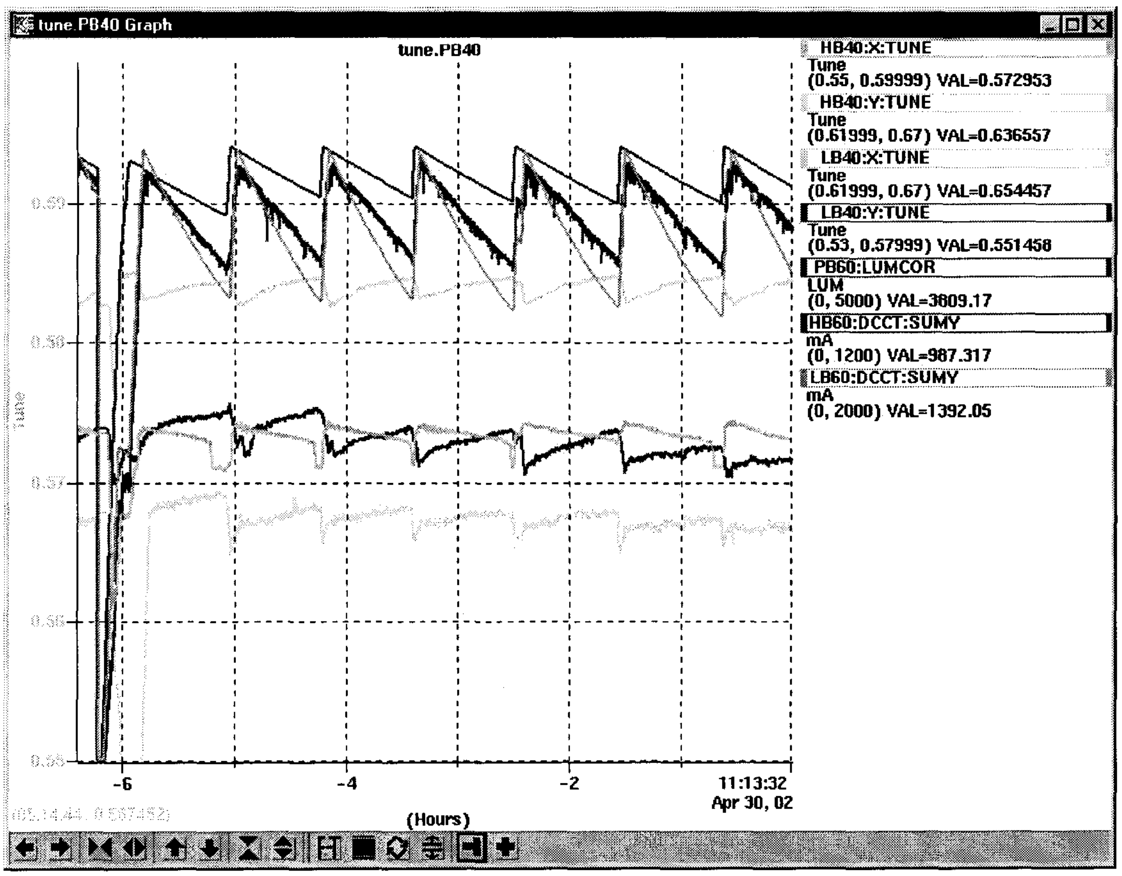

FIGURE 6. EPICS strip chart showing over six hours of tune tracking, through several collide-and-fill cycles and one beam abort. The traces are, from the top: HER current, on a scale of 0–1200 mA; LER current, 0–2000 mA; luminosity (overlapping the LER current and noisier), 0–5×10^{33} cm^{-2}·s^{-1}; LER x tune; LER y tune (sloping upward); HER x tune (downward); and HER y tune. The tunes all have a full-scale range of 0.05, but with different midpoints.