A Longitudinal Multibunch Feedback System for PEP*

H.-D. Nuhn, Y. Sun, H. Winick, W. Xie† R. Yotam
Stanford Synchrotron Radiation Laboratory, P.O. Box 4349, Bin 69, Stanford, CA 94309-0210
H. Schwarz
Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309-0210
and P. Friedrichs
Siemens Medical Laboratories, Inc.

Abstract

A bunch by bunch feedback system to suppress longitudinal multibunch instabilities for PEP has been under development by the Stanford Synchrotron Radiation Laboratory (*SSRL*) and *SLAC*. The system is designed to operate on up to 18 equally spaced electron bunches for synchrotron radiation applications or up to 9 electron by 9 positron bunches for colliding beam operation. As an initial step in developing a very capable multi-bunch stabilizer, the system, which is based on a de-Qed 850 MHz 3-cell cavity, should enable stable storage of a total current of about 36 mA in about 18 bunches at 7 GeV in low emittance mode for synchrotron radiation research. This is based on observed single bunch limits of about 2 mA in the low emittance mode at 7 GeV. At higher electron energy, and/or with modifications to the low emittance lattice, it is likely that even higher currents could be achieved, ultimately limited by transverse instabilities.

I. Introduction

PEP has characteristics that are unique in the U.S. which give it extreme capabilities as a high luminosity e^+e^- colliding beam facility as well as a high brightness X-ray synchrotron radiation source [1][2]. Detailed characterization of the ring and undulator beams were carried out during a low emittance run in 1987 [3]. This run gave clear evidence that the PEP ring and the present photon beam lines offer a significant increase in performance over other sources. In particular, emittances of 4 and 6 nm-rad were measured at 7.1 GeV at low current. Stable currents of 10-15 mA in many bunches were achieved during this run. Both single and multi-bunch instability limits were observed. The thresholds for these instabilities must be increased in order for PEP to reach its full performance potential as a synchrotron radiation source.

The consensus of a workshop [4], held to review the results of the low emittance run and to plan future improvements on PEP, was that a wide-band longitudinal feedback system was the most effective approach to raising the levels of stable stored current in PEP in dedicated low emittance operations towards the desired 50-100 mA. It may be necessary to also implement a transverse feedback system to reach the highest levels.

II. Longitudinal Multibunch Instability

Particle bunches generate electromagnetic wake fields when traveling through a vacuum chamber. In cavity-like structures the Fourier components of these fields that correspond to resonant frequencies oscillate for some time depending on the Q of the resonances. Fields generated by a bunch that passes through the cavity with its center of charge not at the synchronous phase, i.e. performing coherent synchrotron oscillations, can excite coherent synchrotron oscillations in trailing bunches, thus leading to instabilities. The growth rate of these instabilities increases with the bunch current. For low currents natural damping mechanisms like synchrotron radiation keep the oscillations from growing. The excitation process leads to an instability above the threshold current for which the growth time of the multibunch instability τ_{inst} is equal to the damping time τ_{rad}. Theoretical calculations for τ_{inst} in PEP using the ZAP code as well as numerical simulations give unsatisfactory low confidence levels since they depend on the data for the resonances in the 120 main PEP cavity cells. Neither the shunt impedances nor the tunes of these resonances are very well know. During the low emittance run a threshold above 5 to 10 mA has been observed at 7.1 GeV (τ_{rad} = 37 msec). By scaling conservatively from this number we estimate growth times at 100 mA total beam intensity between 2 msec at 7.1 GeV and 3.6 msec at 13 GeV.

III. Detection and Phase Measurement

The bunch-by-bunch feedback system, described in this paper, measures the instantaneous phase of each bunch with respect to the ring master oscillator and provides a correction voltage in each bunch via a cavity. There are two possible approaches to the measurement of longitudinal motion: (1) direct measurement of the phase of each bunch and (2) measurement of the transverse displacement of each bunch in a region of the storage ring with nonzero dispersion. The second approach requires signal processing to separate the betatron motion from the transverse displacement due to longitudinal motion. The direct phase measurement approach has been selected. The system is designed to handle up to 18 equal separated electron bunches or up to 9 electron by 9 positron bunches for a colliding beam mode of operation, proposed by M. Donald and J. Paterson in 1990. This implies a minimum time interval between bunches of 408 nsec. The block diagram of the feedback electronics is given in fig. 1.

A. Pickup Device

The pick up device is a Four Button Beam Position Monitor (BPM), of the type that is used in the PEP ring. The BPM produces a signal every time an electron or positron bunch passes by. The induced signal amplitude is proportional to the distance of the beam from the button and to the beam intensity. If all four buttons are used and the sig-

*Work supported by the Department of Energy, Office of Basic Energy Sciences, Division of Material Sciences.

†Now at the SSC Laboratory, 2550 Beckleymeade Avenue, Dallas, TX 75237.

0-7803-0135-8/91$01.00 ©IEEE

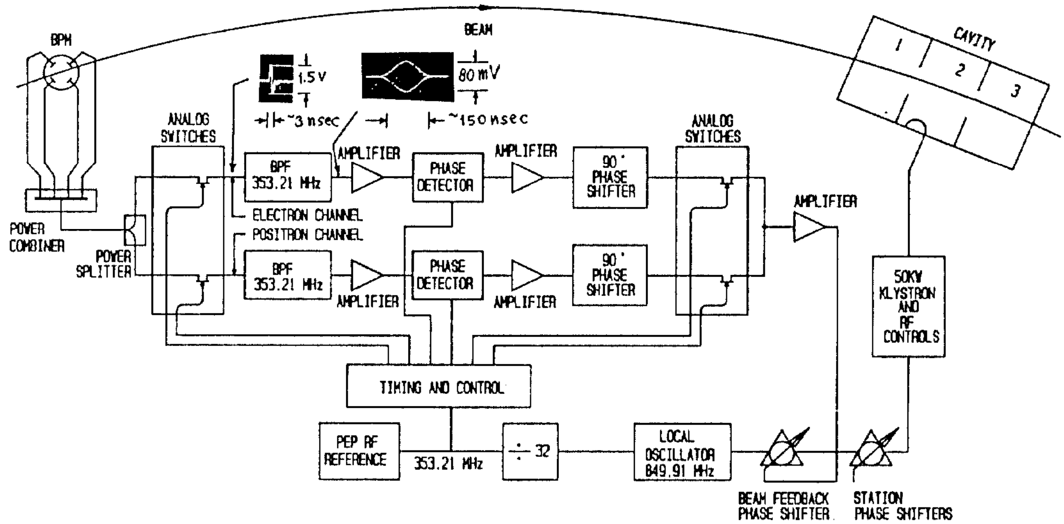

Figure 1
Block Diagram of the Feedback Electronics

nals are transferred through cables and combined into one signal, the signal amplitude will be fairly independent of the beam position. However, each button may contribute a different phase depending on its cable length and phase errors produced by the combiner. It is desired to have a stable signal both in amplitude and phase. The required cable length is 40 m, and the maximum measured phase difference due to the existing variations in the cable length and the combiner phase errors is 5.2°. A special feedback loop is implemented to reduce constant or slowly varying phase offsets.

The peak voltage at the button is given by

$$V_{peak} = \tilde{V}_{peak} \frac{4\alpha}{360^\circ} = \frac{Z_0 \lambda \, q \, e^{-1/2}}{\sqrt{2\pi}\, \sigma^2 v} \frac{4\alpha}{360^\circ} \qquad (1)$$

Z_0	$= 50\ \Omega$	Characteristic Impedance.
λ	$= 0.01$ m	Length of the Beam Position Monitor.
σ	$= 40$ psec	Length of the Electron Bunch.
α	$= 30^\circ$	Height of a BPM Button.
q	$= 14.7$ nC ≈ 2 mA	Charge per Electron Bunch.
v	= c	Speed of the Electron Bunch.

The induced high voltage ($V_{peak} = 1200$ V) at the button is attenuated significantly and the narrow signal is widened at cable end. This is mainly due to the coaxial-cable skin effect.

B. Phase Detection

A direct measurement of the time of arrival is not practical because the required resolution is in the range of picoseconds. Converting from time domain to frequency domain, the BPM signal contains harmonics of the beam revolution frequency of 136 kHz well into 1 GHz. If the 2596 harmonic is chosen, a direct phase comparison with the PEP ring RF of 353.21 MHz is possible and will yield the desired beam phase. Since the feedback system is designed to suppress longitudinal oscillations of both electron and positron bunches, two separate channels which include analog switches, input band pass filters, phase detectors, and amplifiers had been built. The electron and positron bunches can be singled out by switching the BPM signal with high speed analog switches. The conversion from time domain to frequency domain, after the analog switches, is done by applying the signals to an eight stage Bessel type band pass filter. This filter has been chosen because of its characteristics in the time domain. The band pass filter was designed with a center frequency of 353.21 MHz and a bandwidth of 10 MHz. Using SPICE, the time and frequency responses of the filter to the BPM signal have been simulated. The response to a ≈ 3 nsec BPM input signal is a ringing signal which decays after ≈ 150 nsec and its center frequency is 353.21 MHz. This signal is then used as input to the phase detector. The filters have been tested with inputs from the BPM and performed as expected.

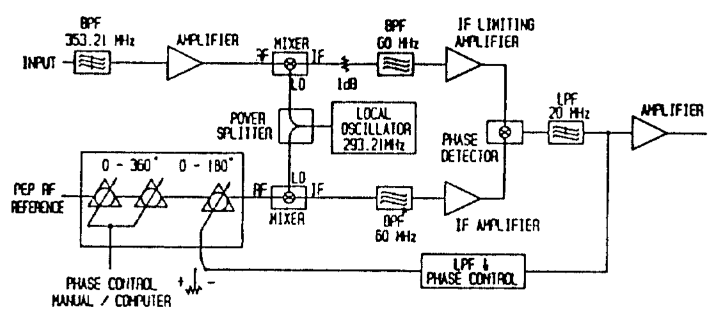

Figure 2
Schematic of the Phase Detector

The requirements for the actual phase detector are: phase resolution of better than 0.5°, and high relative phase stability and accuracy over the range of at least a factor of 10 in beam intensity. The most suitable approach was selected to be a heterodyne system with an IF at 60 MHz, limiting amplifiers at the IF frequency with minimum phase variation over the limiting range, and an analog phase detection scheme at the IF frequency using mixers.

The phase measurement circuit includes a special loop to eliminate constant (or slowly changing) phase offsets at the output of the phase detector. Such offsets are the consequence of the mixers' characteristics, a change in the phase between the PEP master oscillator and the BPM signal, or a change in phase due to the contribution of the cables and other components (fig. 2).

IV. Signal Processing

The damping of the coherent oscillations is done by applying an energy correction to each bunch, i.e. damping the energy oscillations. The energy oscillations are the time derivative of the phase oscillations whose amplitude is measured by the phase detector. In our case the time derivative is equivalent to a 90° phase shift. The signal processing includes the implementation of a 90° phase shifter. The intention is to use a digital finite response filter (FIR), which provides some noise reduction on the raw signal in addition to the 90° phase shift. A 90° phase shift is also required from the system stability point of view.

V. Energy Correction

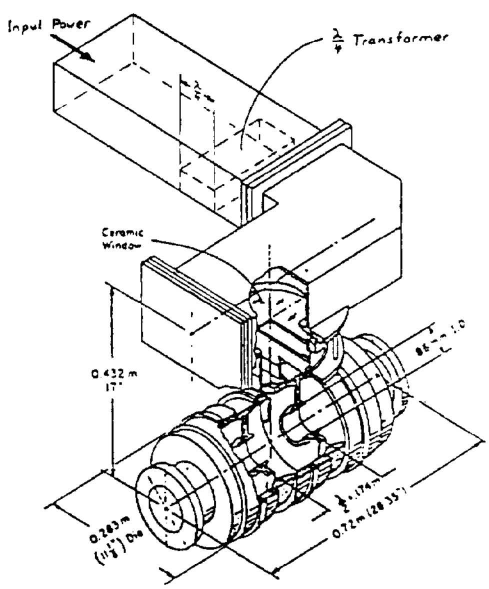

Figure 3
3 Cell Cavity with Waveguide Transformer

A. RF System

The frequency for the RF system was chosen to coincide with the 6237th harmonic of the PEP revolution frequency at an operating frequency of 849.91 MHz. Major components are used from the PEP six bunch longitudinal feedback system[5]. As amplifier a commercial TV klystron is utilized which can provide up to 50 kW cw output power and a 1 dB bandwidth of 7.5 MHz. A circulator directs the considerable reflected power form the over-coupled cavity into a 40 kW load. Typical feedback loops guarantee long term stability of amplitude and phase in the cavity without interfering with the fast feedback signals, for which the system is being designed.

B. Feedback Cavity

To provide the longitudinal kick, the three cell aluminum cavity of the PEP six bunch longitudinal feedback system is reused. It was originally built for a bunch spacing of 1.2 μsec for which the loaded Q of the assembly was reduced to 1350 by over-coupling through a large coupling iris. For the application now under consideration the minimum bunch spacing is only 408 nsec and the Q had to be lowered further. Since the coupling iris was not accessible because it is blocked by the ceramic window, a quarter wavelength transformer was placed in the feed waveguide outside the window one wavelength away form the iris (see Fig. 3). By choosing the impedance of the quarter wavelength transformer to be half the impedance of the waveguide the loaded Q of the cavity could be lowered to about 330 as expected. Under this loading condition the resonance of the π-mode gets broad enough to start overlapping with the $2\pi/3$-mode and thus puts a limit to the attempt to broaden the bandwidth of the cavity. The inter-

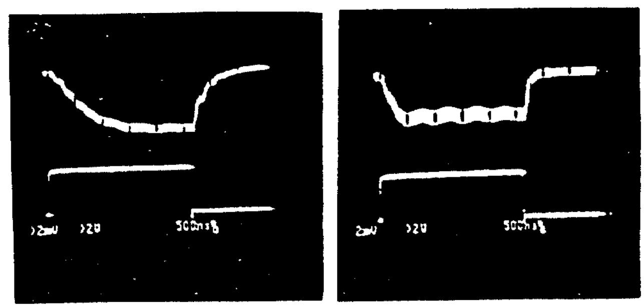

Figure 4
Response of the field in cell 3 for a step function drive into cell 2, .5 μsec/div., a) Q=1350, b) with waveguide transformer, Q=330

cell coupling would have to be increased, if one wanted to reduce the Q further, which is not practical in a completed cavity. A measurement of the response of the cavity field in cell 3 to a step function in the drive to cell 2 indicates a response time (10 – 90 %) of about 300 nsec (Fig. 4) which is sufficient for the feedback to affect individual bunches with a 408 nsec spacing.

VI. Status

The phase detector has been fabricated and tested, partially with beam. The energy correction system is ready to go. Work has been done in developing the signal processing and timing system.

This work has been put on hold with the SLAC decision to not operate PEP during FY 1991 due to a large budged cut. Work will resume when the future operation of PEP is clarified. In the meantime we are shifting our attention to feedback systems on SPEAR, which is now a fully dedicated light source with a dedicated 3 GeV injector synchrotron.

VII. References

[1] A. Bienenstock et al.,. **60**, 1393-1398 (1989).
[2] J. Paterson,. Proc. of the 1989 Part. Acc. Conf.
[3] S. Kramer et al.,. Proc. of the 1989 Part. Acc. Conf.
[4] H.-D. Nuhn, H. Winick edt., 1988. SSRL Rep. 88/06.
[5] M. Allen et al.,. IEEE, NS-28, No. 3, 2317.