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Beam Bunch Feedback

G. Lambertson
Accelerator and Fusion Research Division

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Lecture presented at the
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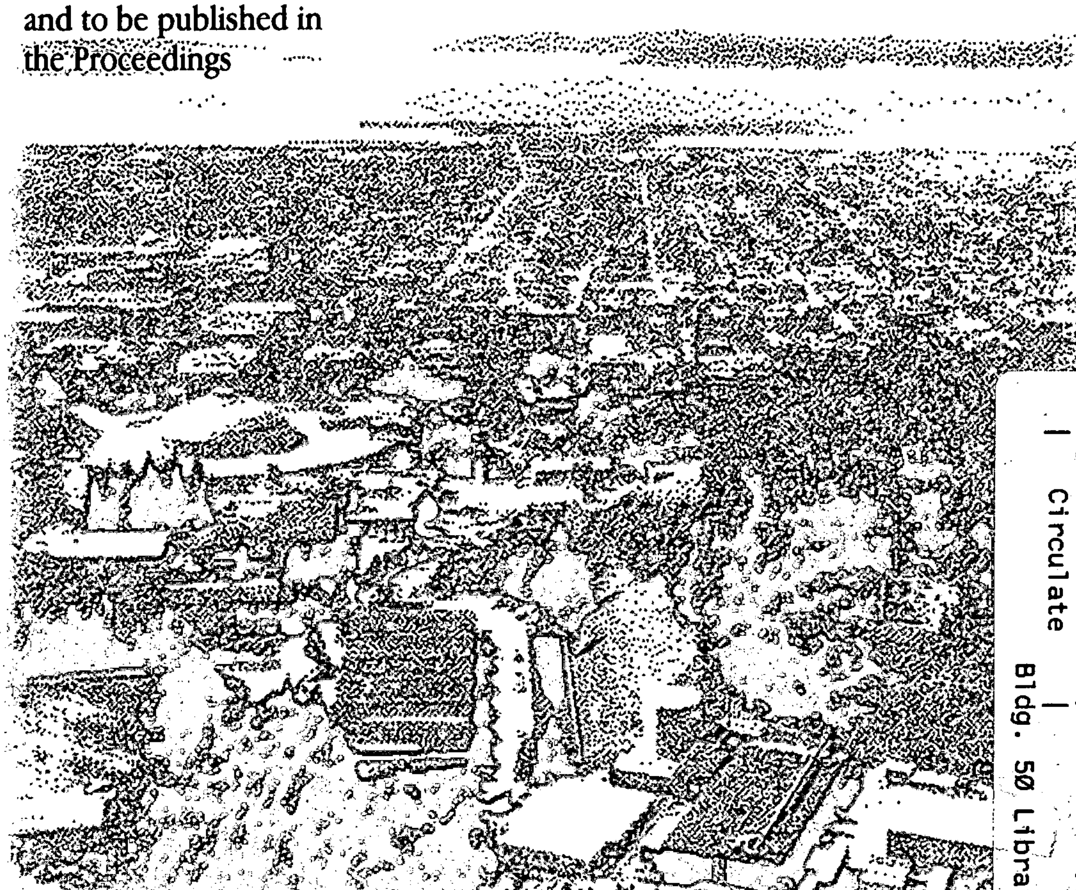

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Beam Bunch Feedback*

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Beam Bunch Feedback

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1 Introduction

When the electromagnetic fields that are excited by the passage of a bunch of charged particles persist to act upon bunches that follow, then the motions of the bunches are coupled. This action between bunches circulating on a closed orbit can generate growing patterns of bunch excursions. Such growth can often be suppressed by feedback systems that detect the excursion and apply corrective forces to the bunches. To be addressed herein is feedback that acts on motions of the bunch body centers. In addition to being useful for suppressing the spontaneous growth of coupled-bunch motions, such feedback can be used to damp transients in bunches injected into an accelerator or storage ring; for hadrons which lack strong radiation damping, feedback is needed to avoid emittance growth through decoherence. Motions excited by noise in magnetic fields or accelerating rf can also be reduced by using this feedback.

Whether the action is on motions that are transverse to the closed orbit or longitudinal, the common arrangement is sketched in Fig. 1. Bunch position is detected by a pickup and that signal is processed and directed to a kicker that may act upon the same bunch or some other portion of the collective beam pattern. Transverse motion is an oscillation with angular frequency $\nu_\perp\omega_0$ where ω_0 is the orbital frequency $2\pi f_0$. Longitudinal synchrotron oscillation occurs at frequency $\omega_s = \nu_s\omega_0$. The former is much more rapid, $\nu_\perp$ being on the order of 10 while ν_s is typically about 10^{-1} to 10^{-2}.

1.1 Coupled-bunch motions

The coupled-bunch (c.b.) motions are conveniently described and analyzed [1] in terms of azimuthal harmonic patterns, or modes characterized by an integral number n of sinusoidal cycles per turn. Viewed at one instant, excursion of M equally spaced

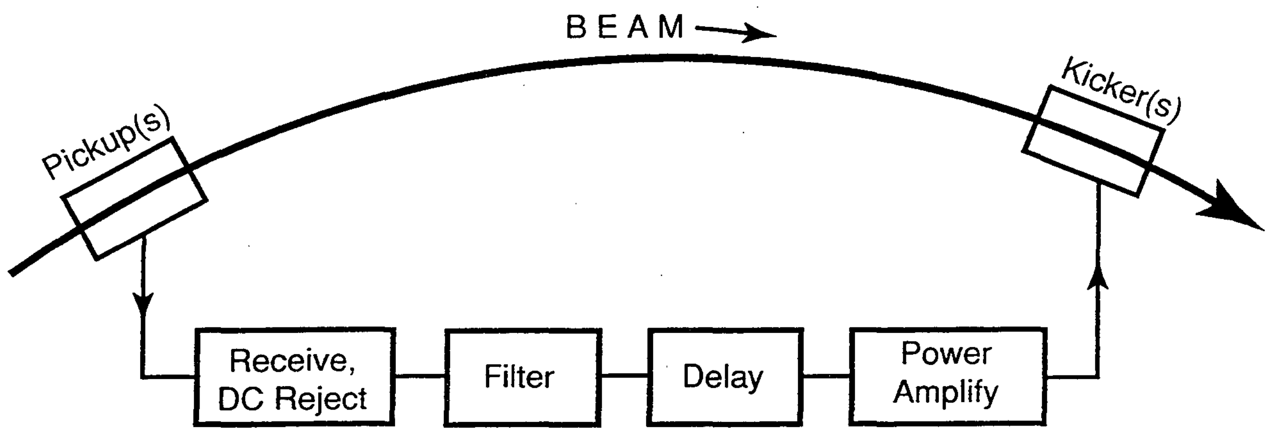

Figure 1: Schematic arrangement of feedback components. The pickup-to-kicker distance may be as great as many turns.

bunches in mode n with amplitude X_n lies on a locus $X_n cos 2\pi n\theta$. Each bunch then oscillates with frequency $\nu\omega_o$ making the position of the ith bunch be

$$x_i = x_n e^{j\nu\omega_0 t} e^{j2\pi ni/M} \tag{1}$$

This ith bunch passes azimuth θ when $\omega_0 t = \theta + 2\pi i/M$. The velocity of the bunch is, of course,

$$\dot{x}_i = j\nu\omega_0 x_i \tag{2}$$

There are M possible moles labelled 0 through $M-1$.

The succession of bunch excursions at a detector or a kicker at azimuth θ is expressible as

$$x(t,\theta) = X_n \sum_i e^{j(\nu\omega_0 t + 2\pi ni/M)} \delta\left(t - \frac{\theta}{\omega_0} - \frac{2\pi i}{M\omega_0}\right) \tag{3}$$

or equivalently

$$x(t,\theta) = X_n \frac{M\omega_o}{2\pi} \sum_{\rho=-\infty}^{\infty} e^{-j(pM+n)\theta} e^{j(pM+n+v)\omega_0 t} \ . \tag{4}$$

in which t is a continuous variable. The fourier transform of this "signal" is, of course,

$$x(\omega) = X_n \frac{M\omega_0}{2\pi} \sum_{n=1}^{\infty} e^{-j(pM+n)\theta}\ \delta\left[\omega - (pM + n + \nu)\,\omega_0\right] \ . \tag{5}$$

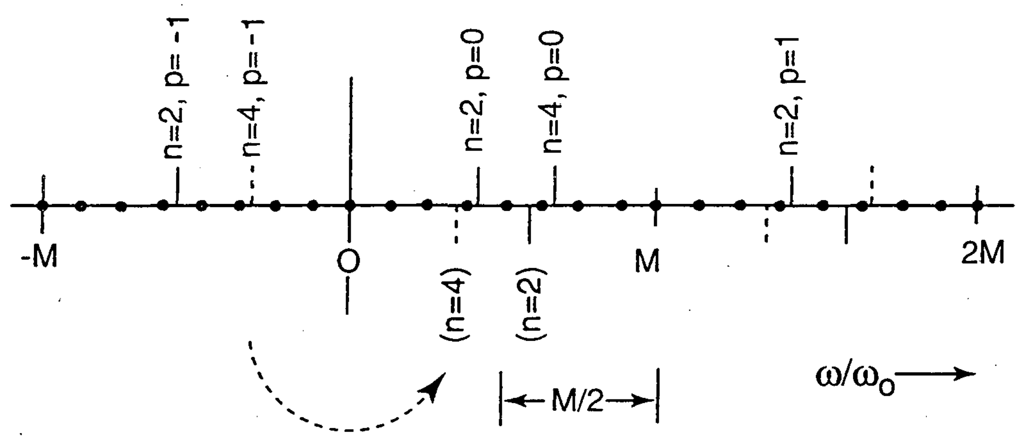

Figure 2: Plot of $\omega(n,p)$ for M=8, ν=1+$\Delta\nu$=1.3, and n=2 and 4. Negative ω's are shown below the line in the positive domain.

A pickup produces a signal with this spectrum of sidebands of integral orbital harmonics $pM\omega_o$. The frequencies that are negative appear as lower sidebands (see Fig. 2). Thus, signals from all M possible modes will appear in each frequency interval $\frac{1}{2}M\omega_o$, one half the bunch-passage rate. A kicker will act upon the bunch velocities, which are

$$\dot{x}(t,\theta) = j\nu\omega_0 x(t,\theta) \quad . \tag{6}$$

Note that these are not $dx(t,\theta)/dt$.

1.2 Delay and Phase

A transverse kicker can alter transverse velocity; a longitudinal kicker alters energy. But pickups detect transverse position or longitudinal time-of-arrival (phase φ). Therefore a conceptually simple plan for feedback would detect a bunch excursion, then delay the signal one-quarter oscillation and deliver a corrective kick to the same bunch. This scheme is called bunch-by-bunch feedback. But, particularly in the longitudinal case, it calls for a long accurately timed delay that may also need broad bandwidth to deal with many modes. Only recently have we had the technology to make long delays at a high bunch rate using digital processing or fiber optics. An alternative is mode-by-mode feedback in which only the sideband signal for a mode of interest is phase-shifted as required and fed back reasonably promptly. We examine the phase and delay requirements for these cases in what follows.

Feed the signal x for mode n from a pickup at $\theta = 0$ to a kicker to modify $\dot{x}$ at azimuth θ downstream. Amplify and phase-shift the signal by overall complex factor A and delay by time Δt. The per-turn change in $\dot{x}$ is thus

$$\Delta\dot{x}(t,\theta) = -A(\omega)\, x(t-\Delta t, 0) \quad . \tag{7}$$

Assume that the damping rate of the mode amplitude X_n is small relative to ω_0 and thus the average effect of $\Delta\dot{x}$ over time is a change ΔX_n per turn. Using Eqs. (4) and (6) we get

$$j\nu\omega_o 2\Delta X_n \sum_p e^{-j(pM+n)\theta} = -X_n \sum_p A e^{-j(pM+n+\nu)\omega_o\Delta t} \tag{8}$$

or

$$\frac{\Delta X_n}{X_n} = -\frac{1}{j2\nu\omega_o}\sum_p A(\omega)\, e^{j(pM+n+\nu)(\omega_o\Delta t-\theta)} e^{j\nu\theta} \tag{9}$$

For damping we want this growth rate to have a negative real component for the sum of all sidebands $\omega(p,n)$ for each mode n. Note that A may be assumed to have the usual property $A(-\omega) = A^*(\omega)$.

The bunch-by-bunch case has delay $\omega_o\Delta t = \theta$ and $\nu\theta = \pi/2$. It is apparent that with this we require only that for each mode the sum of $A(\omega)$ at the sideband frequencies within its bandpass have a real component that is positive.

For the more general case where $A(\omega)$ must provide some of the needed phase shift, we must examine the requirements for the pair of sidebands at $\pm\Delta\nu$ from each orbit harmonic $q\omega_o = (pM + n + \nu_o)\,\omega_o$. We ask that

$$\begin{aligned}(q+\Delta\nu)(\omega_o\Delta t-\theta)+\nu\theta+\angle A(q+\Delta\nu) &= \pi/2,\\ (-q+\Delta\nu)(\omega_o\Delta t-\theta)+\nu\theta+\angle A(-q+\Delta\nu) &= \pi/2\ .\end{aligned} \tag{10}$$

From these we find, using $\angle A(\omega) = -\angle A(-\omega)$,

$$\angle A(q+\Delta\nu) - \angle A(q-\Delta\nu) = \pi - 2\nu\theta - 2\Delta\nu(\omega_o\Delta t-\theta) \quad . \tag{11}$$

In the absence of special values of θ and δt, the electronics must provide a phase shift approaching π between upper and lower sidebands. For prompt or narrow-band feedback, filters are used at each orbit harmonic for this function.

To feed back all the possible M c.b. modes with the bunch-by-bunch scheme, the circuits must have a bandwidth of at least $\frac{1}{2}M\omega$. If the feedback is needed for only a reduced set of modes, the bandwidth may be reduced providing the phase shifts versus gain avoid positive feedback for some modes. Reduced bandwidth allows economy in cost of delay, power amplifiers, and other components.

Mode-by-mode systems allow, even require, narrow-band circuits for each mode of interest. The separate mode filters often operate at a downshifted frequency and allow one to customize the response. For hundreds of modes the multiplicity becomes cumbersome.

2 Transverse Systems

2.1 Design Basis

With negative resistive feedback, a transverse system will provide a damping rate $1/\tau$ defined as follows:

$$\frac{1}{\tau_n} = -\frac{1}{X_n}\frac{dX_n}{dt} = -f_0\frac{\Delta x'_\kappa}{2x'_\kappa} = f_0 G \tag{12}$$

where

$G =$ average feedback gain per turn, and

$\Delta x'_\kappa =$ angular deflection per turn at the kicker corresponding to an angular deviation x'_κ .

The factor 2 [also seen in Eq. (9)] arises from averaging over a sinusoidal motion. Any radiation damping will effectively add to this rate. To suppress a growing c.b. mode, the combined damping rate must exceed the mode growth rate; this rate determines the required gain. The growth rate is given by [1, 2]:

$$\frac{1}{\tau_n} = -\frac{I_0 f_0}{2\beta\ E/e}\sum_{p=-\infty}^{\infty}\beta_\perp Z_\perp\left(\omega_{np}\right) S\left(\omega_{np}\right) \tag{13}$$

where

$I_0 =$ average beam current

$E/e =$ particle energy (volts)

$\beta = v/c$

$Z_t(\omega) =$ transverse beam impedance at frequency $\omega_{np} = (pM + n + \nu)\,\omega_o$

$\beta_\perp =$ reference $\beta_\perp$ for total $Z_\perp$ in ring (usually R/ν)

$S(\omega) =$ shape factor for strength of coupling to bunch shape at frequency ω_{np}. $\left(\text{For gaussian, } S = e^{-(\omega\sigma_t)^2}.\right)$

This shape factor S (not the same as F in Refs. 1 and 2) terminates the summation as λ becomes less than the bunch length. In this summation the c.b. frequencies are upper sidebands at $\Delta\nu\omega_0$ above the orbit harmonics $(pM + n + \nu_0)\,\omega_0$ that extend over negative as well as positive frequencies. Because the real part of $Z_\perp$ is an odd function of ω, c.b. frequencies that fall in the negative domain (which would appear as negative sidebands in the positive domain) excite a positive growth rate from a resistive $Z_\perp$. [The same "upstream wave" mechanics was seen in the phase requirements of Eq. (11)].

Principle contributors to $Z_\perp$ are resonances in cavities and other structures and the resistivity of the beam-tube wall. The resistive-wall impedance is stronger in rings of large circumference; it varies with frequency as $\omega^{-1/2}$. In proton rings having little radiation damping, bunch oscillations caused by magnet motions can cause emittance growth. To suppress this, gain as large as allowed by the input noise is needed.

The required effective voltage kick per turn $V_\perp$ is proportional to the desired damping rate and to the amplitude of bunch motion:

$$V_\perp = X\frac{2\beta^2 E/e}{\tau f_0 \beta_\kappa} \quad . \tag{14}$$

Here β_κ is the transverse β-function at the kicker location. Equation (12) can be applied to a single bunch with amplitude X_i or to a mode with amplitude X_n. In the former case, perhaps a number of mode amplitudes could add. The single-bunch case is directly applicable in damping excursions of an injected beam where rapid damping is desired to reduce emittance growth.

2.2 Components

The pickups for transverse feedback may be capacitive buttons or, for longer bunches, striplines. To maximize signal, one may detect in any frequency band up to the lowest cutoff for TE waves in the beam tube. In the difference signal there will be unwanted harmonics of the orbital frequency f_0 that arise from pickup imbalance or orbit offset. This signal if fed back will not disturb the beam, but it may overload digital circuits or the power amplifier. The harmonics also obscure the betatron signals that one may want to observe directly. Rejection of the d.c. level at baseband does not remove higher harmonics. Notch filter or feedback circuits are useful here. A bunch that at the kicker crosses the centerline with angle x'_κ would at a pickup upstream $\Delta\psi$ in betatron phase have been detected with excursion x_p given by

$$x_p = -x'_\kappa \sqrt{\beta_p \beta_\kappa}\, sin\Delta\psi \quad . \tag{15}$$

If the pickup is, conveniently, about a turn upstream from the kicker, the betatron phase advance $\Delta\psi$ may change significantly with any operational changes in $\nu_\perp$. For that reason or other considerations, two pickups approximately $\lambda_\perp/4$ apart may be used and their signals combined in an adjustable ratio to give the desired $sin\Delta\psi = \pm 1$. A notch filter, if present, adds a phase shift that must also be included. An alternative is to use digital phase control with a single pickup. A kicker consisting of stripline electrodes on opposing sides of the aperture has a shunt impedance $R_\perp$ given by [3]

$$R_\perp = 2Z_L \left(\frac{2g_\perp}{kh} sin\ k\ell \right)^2 \tag{16}$$

$$\begin{aligned} \text{where } Z_L &= \text{line impedance of each strip,} \\ \ell &= \text{length,} \\ h &= \text{gap between strips,} \\ k &= \omega/c, \\ g_\perp &= \text{coverage factor} = E_\perp / \left(\Delta V/h\right), \end{aligned}$$

with $E_\perp$ being the TEM field at the orbit with voltage ΔV between plates. To deliver voltage kick $V_\perp$ using N_κ kickers requires power

$$P = V_\perp^2 / 2N_\kappa R_\perp \quad . \tag{17}$$

Because the kicker is strongest at low ω, economy of amplifier cost argues for using the lowest band of c.b. frequencies; this starts at $(1 - \Delta\nu)\,\omega_0$ and extends to $\frac{1}{2}M\omega_0$. Strong damping for the lower frequencies is also desirable for opposing the transverse resistive-wall impedance and perhaps injection transients. But for a broad-band amplifier, the low $(1 - \Delta\nu)\,\omega_0$ may be straining amplifier technology. In the next c.b. band, $\frac{1}{2}\ M\omega_0$ to $M\omega_0$, the power efficiency of a necessarily shorter kicker is less by a factor 10 for the frequencies near $M\omega_0$ which are driven by resistive-wall impedance. Two sequential stripline pairs, connected in series-opposed form a kicker with $R_\perp$

about 4 times greater at $M\omega_0$. Broadband power amplifiers for transverse feedback cost typically about \$120 per watt.

We are also concerned with the beam impedance the kickers present and with the heating of the electrodes by the beam-induced currents. The kicker's transverse beam impedance is $kR_\perp/4$ except if it is a cavity with matched load for which it is $kR_\perp/2$; any longitudinal impedance also takes power from the beam bunch current. Power extracted by stripline shunt impedances is delivered to an external terminator that is readily cooled, but parasitic losses may heat the electrodes. (Striplines of length $\lambda/2$ at the bunch rate Mf_0 have zeroes at harmonics of the bunch rate, greatly reducing the picked-up power.) Image currents induced in the electrodes also cause heating. Cooling by water circuits or improved conduction or radiation to the exterior may be needed. A 3-ampere electron beam in PEP-II is expected to deposit 14 watts from image currents in its transverse kicker; the striplines will be blackened to increase heat radiation, and heat will be conducted through the vacuum feedthroughs.

2.3 Example Systems

Bunch-by-bunch feedback for all modes is being constructed for the PEP-II rings.[4] The low-energy ring of 3.1 GeV has orbital frequency $f_0 = 136$ kHz and bunch rate $Mf_0 = 238$ kHz. The design maximum current is 3 ampere average. The block diagram is shown in Fig. 3.

Pickups are 4-button sets used at $6Mf_0 = 1.43$ GHz. Kickers are stripline pairs operating in the band 13 kHz to 119 MHz. Power amplifiers, 240 watt per kicker, can go to twice that band to allow for possible increase in the bunch rate. Rejection of harmonics from closed-orbit offset is required; this is achieved by adding sum signal as needed to the difference signal before down-converting.

Anticipated growth rates for PEP-II LER have been calculated by using in Eq. (13) the measured rf cavity higher-order modes and calculated resistive-wall impedance. Fig. 4 shows the result. The system is also to be used to eject any bunch as desired by applying maximum gain in reverse.

Injection into PEP-II is at the rate of 1/5 bunch each 1/60 second. This small charge makes injection-error damping very undemanding. With the feedback gain and power set to stabilize a 3-ampere stored beam, the transverse error of the injected pulse drives the amplifier to full power until that error is damped to about 1% of its initial amplitude. The effect of this bang-bang action is shown in the linear-damping region of a computer simulation [5] in Fig. 5. The small and controllable motion excited in a subsequent bunch is also shown.

An example low-frequency damper at the CERN SPS is shown in Fig. 6. This

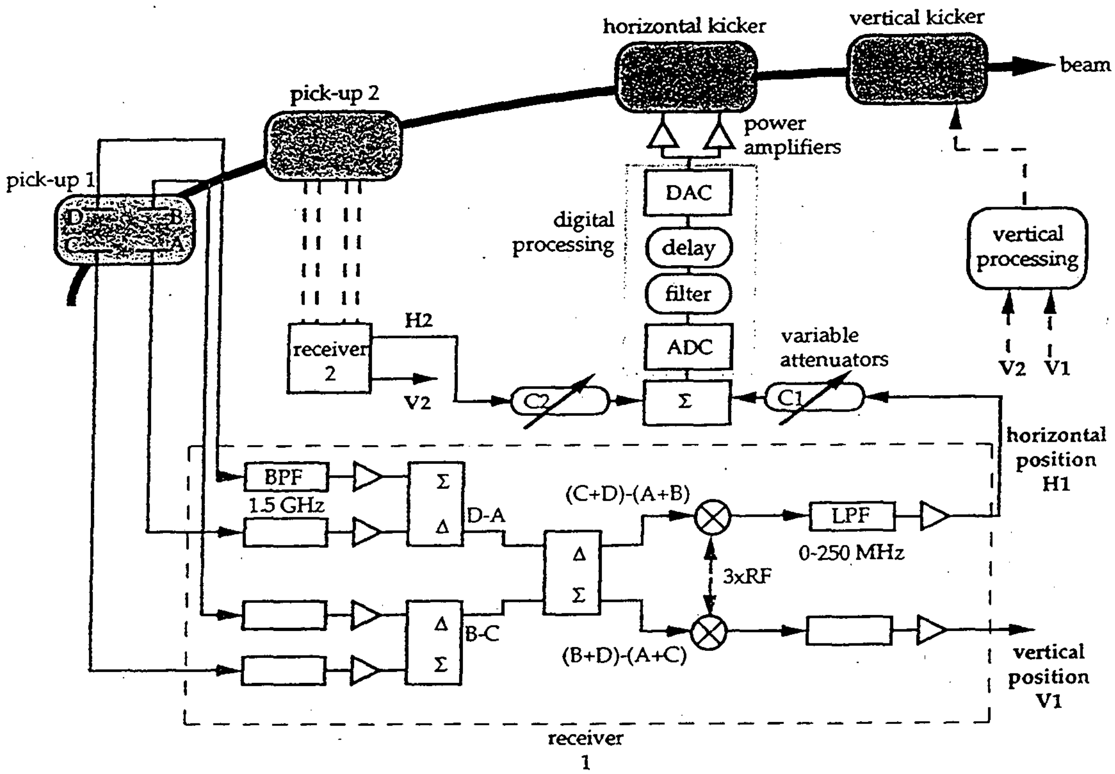

Figure 3: Transverse feedback design for PEP-II.

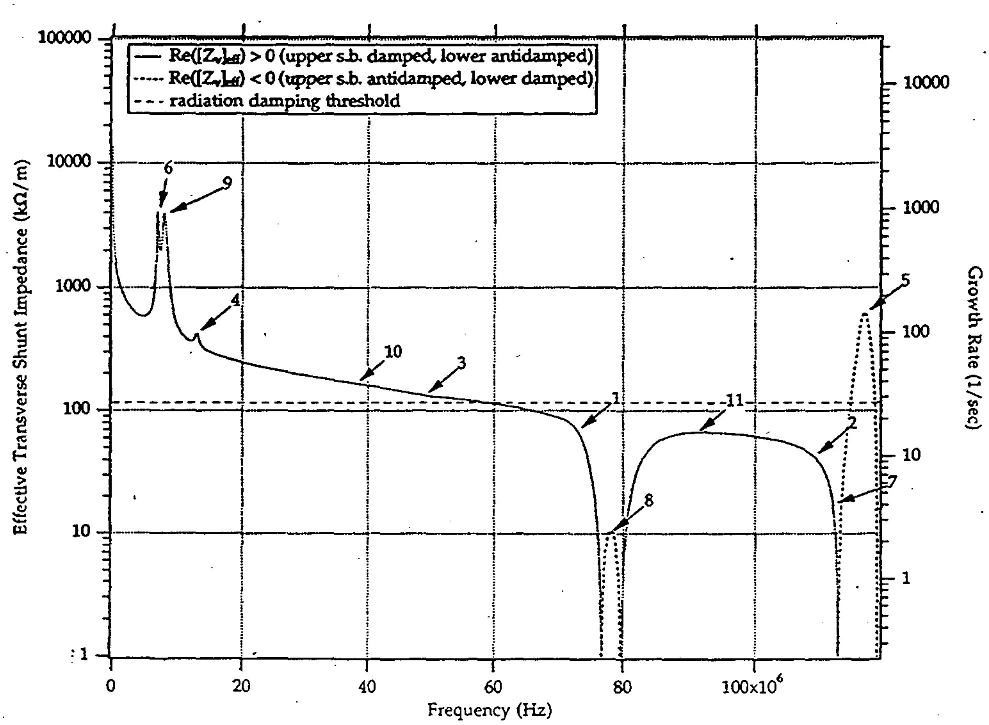

Figure 4: Calculated growth rates for the 1756 transverse modes in the PEP-II low-energy ring for 3-ampere current.

Table 1: Transverse Dampers

Machine	h	M	Mf_0 [Hz]	Frequency band	Kick	V,I, Power	Digital or Analog
$SPS^{4,5}$	4620	4620	200M	3k-10M	E	3kV_p	D
ISR^4	30	20	9.5M	0.1-1.6M	E+B	2.5kW	A
$PSB^{2,3}$	5	5	8M	5k-50M	E+B	100W	A
$PS^{(1),2,4}$	20	20	9.5M	60k-2.5M	E+B	2kW	D
$FNAL\ B^{1,2}$	84	84	53M	0-27M	E+B	100W	A
$FNAL\ M^{1,2}$	1113	1113	53M	0-27M	E+B	5kW	D
$FNAL\ T^{1,2,3}$	1113	1113	53M	0-27M	E+B	5kW	D
$SPEAR\ II^{1,3}$	280	1+1	1.3M	0.0.65M	E+B	2.5kW	A
$NSLS\ B^4$	5	1	10.5M	10-250M	E+B		A
$PETRA^{1,3}$	400	80	10.4M	5-10M	B	1kW	D
$LEP^{1,3,5}$	31320	4+4	45k	0-23M	B	40A_p	D
AA	1	1	1.85M	0.1-25M	E+B	10W	A
$LEAR^{2,3}$	1-2	1-2	3.6M	0.1-70M	E+B		A
$PEP^{1,3}$	2592	6+6	816k	9.4-10.2M	B	20A_p	A
$ALS^{1,3,4,5}$	328	328	500M	0.15-250M	E+B	300W	A
$PEPII(des.)^{1,3,5}$	3492	1746	238M	13k-238M	E+B	300W	A

[1]Bunch-by-bunch. [2]Delay tracking. [3]Closed-orbit suppression.
[4]Notch filter. [5]90° pickup.

bunch-by-bunch system damps the 10% of c.b. modes at lowest frequency to oppose resistive-wall effects and decoherence. A digital filter provides one-turn delay and notch-rejection of orbit-offset signals. Power amplifiers drive electrostatic-plate kickers at 3 kV peak voltage.

Table 1 lists some parameters of transverse systems.[1]

3 Longitudinal Systems

3.1 Design Basis

Phase motions within a longitudinal c.b. mode n with amplitude Φ_n referred to the accelerating frequency ω_{rf} produce the currents $\widetilde{I}_{np}$

$$\widetilde{I}_{np} = jI_0\Phi_n\omega_{np}/\omega_{rf} \tag{18}$$

[1]Much of this Table 1 and Table 2 was presented by F. Pedersen at the 25th Workshop of the INFN Eloisatron Project, Erice, Italy, 1992.

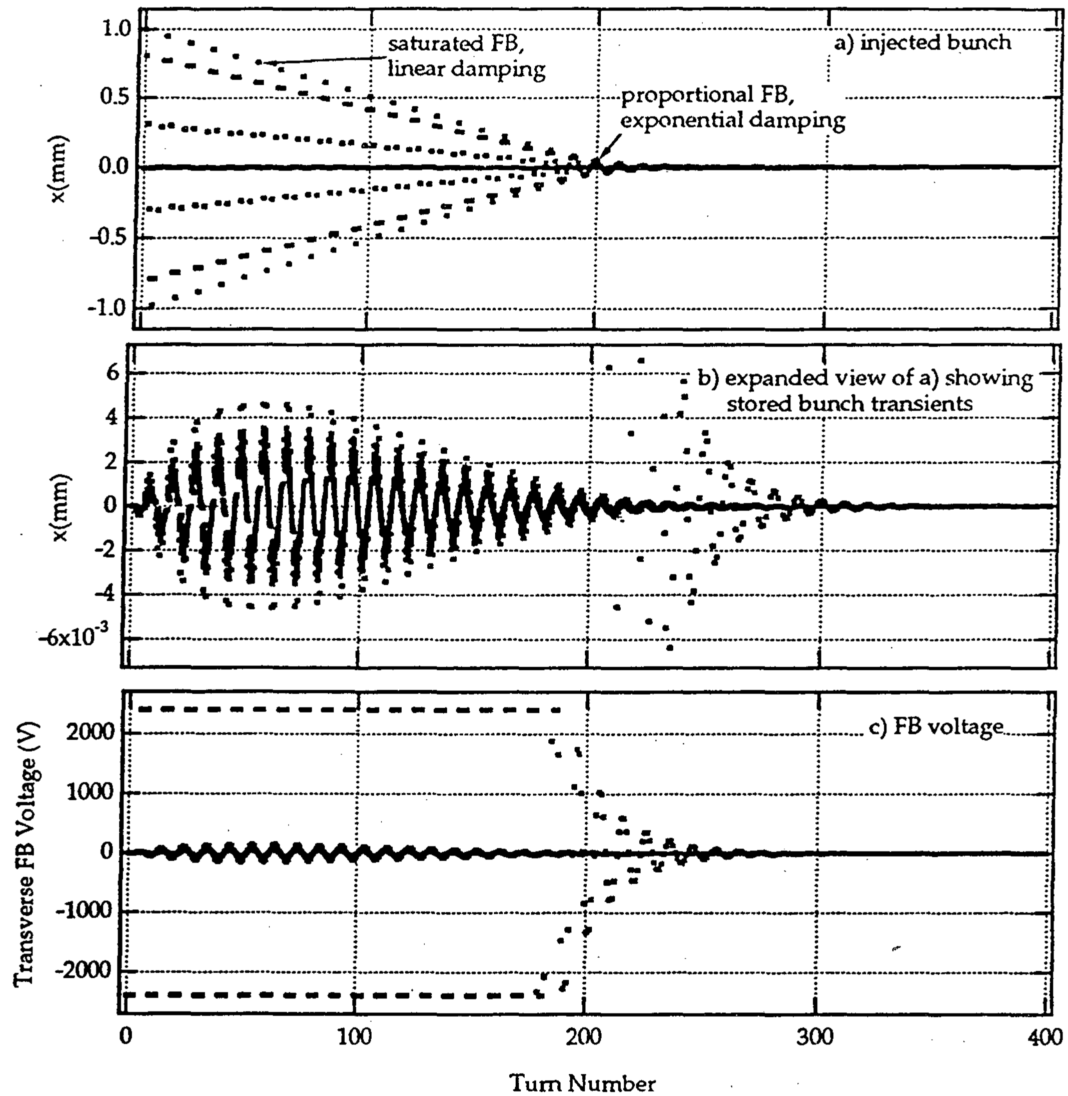

Figure 5: Simulated operation of feedback upon injection of one offset bunch that saturates the kicker amplifier and induces a transient in the following stored bunches.

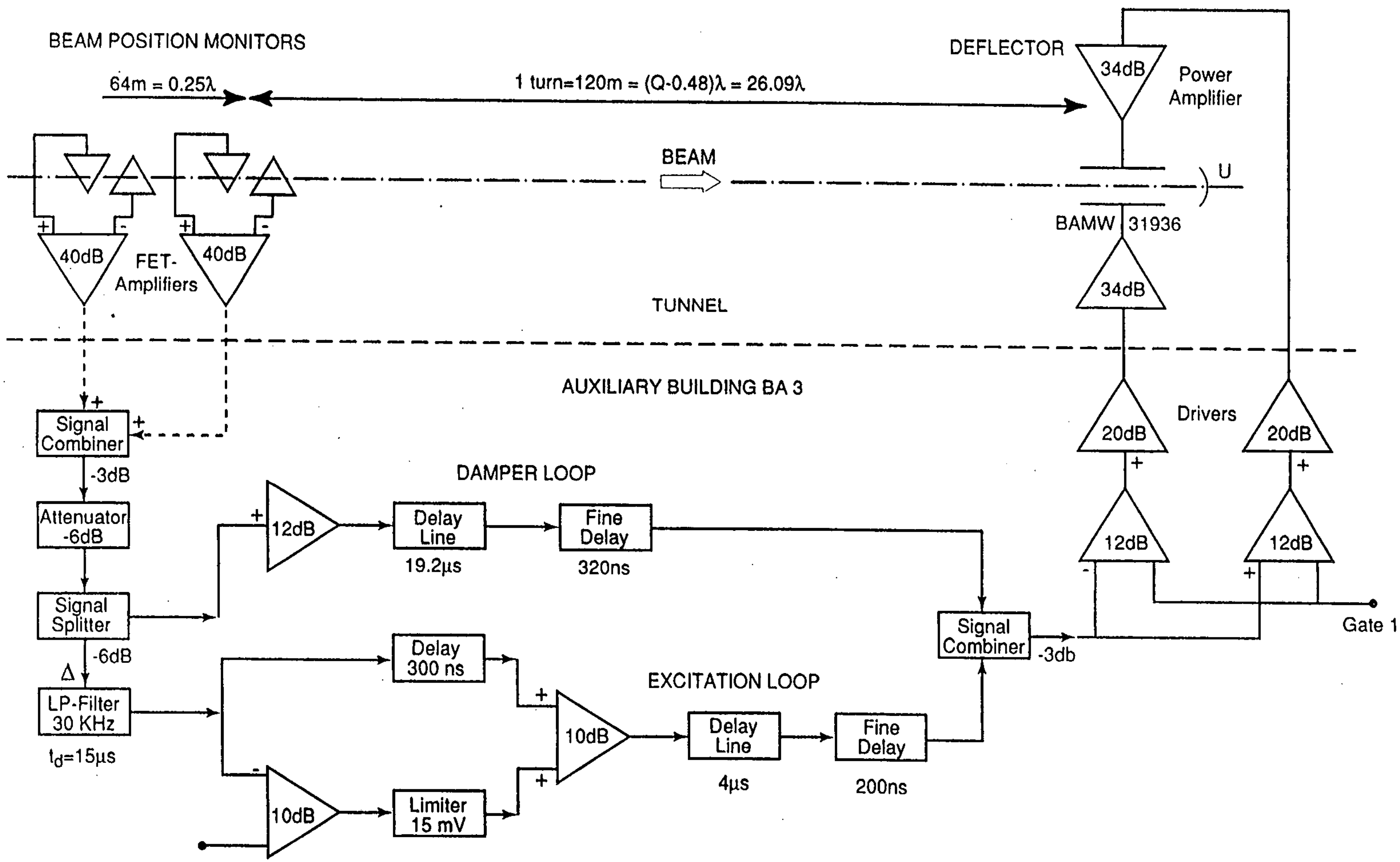

Figure 6: CERN SPS low-frequency damper.

at the c.b. frequencies

$$\omega_{np} = (pM + n + v_s)\,\omega_0 \quad . \tag{19}$$

These currents induce in the longitudinal beam impedance $Z_{||}(\omega)$ the effective voltage

$$V_n = jI_0\Phi_n \sum_{p=-\infty}^{\infty} \frac{\omega_{np}}{\omega_{rf}} Z_{||}(\omega_{np})\, S(\omega_{np}) \quad . \tag{20}$$

The shape factor S [see Eq. (13)] cuts off the series, and negative values of ω_{np} reverse the sign of voltages for frequencies that will appear as negative sidebands in the positive frequency domain. In the resultant growth rate an additional reversal arises from the phase-slip factor η when above transition. Therefore, above transition, resistive $Z_{||}$ drives c.b. growth for upper sidebands. The growth rate is

$$\frac{1}{\tau_n} = \frac{f_{rf}\eta}{2v_s\beta^2 E/c} \frac{imag V_n}{\Phi_n} \quad . \tag{21}$$

Invert this Eq. (21) to find the feedback voltage kick required to produce a damping rate $1/\tau$ for a particular phase excursion. If only a small fraction of the full beam current is injected at one time, its excursion may not drive a strong c.b. growth rate to be overcome by feedback. But a large injected charge will probably call for maximum demand on kicker voltage, although it may not require that over the full band of c.b. frequencies. Of course, if preventing decoherence after injection is a principle concern, that will most likely determine the required voltage and gain spectra. A special consideration is the beam impedance of the acceleration mode of the rf cavities. In a large-radius ring, harmonics of the orbital frequency can fall within the band-width of the fundamental mode. If the cavities are detuned to compensate for beam leading, c.b. modes within this band-width will be very strongly driven unless the beam impedance of the cavities is reduced [6]. This can be accomplished by negative feedback of cavity voltage through the rf drive circuit; an example of this is given below for PEP-II.

3.2 Components

The longitudinal-pickup signal is fed to a phase detector. It can be an advantage for greater sensitivity to detect at a multiple of the rf frequency. Also, a short comb-generator can be used to produce from the bunch pulse a pulse train at the detection frequency. However, the higher frequency reduces the range of phase that can be detected with reasonably linear response. Slow feedback of the average phase to the reference oscillator phase can keep the stable phase at midrange and reject orbit harmonics.

The straightforward bunch-by-bunch scheme requires a delay of 1/4 synchrotron period; a fiber optic delay may be used or digital hardware once the bunch-phase signals are digitized. A shorter delay is allowed if one feeds back the difference between phases separated by an interval of perhaps 30° of the synchrotron cycle. This difference method gives a more prompt feedback if that is desired at the cost of reduced signal/noise ratio. Going toward longer delay would be the use of a FIR filter with a number of taps covering a full synchrotron period. This allows rejection of phase offsets and some control of signals that arrive from modulations of bunch shape. The mode-by-mode feedback may be very prompt except for the delay inherent in the filters required to provide 180° shift between each pair of upper and lower sidebands.

A $\lambda/4$ drift tube or the stripline pair are the most common longitudinal kickers, but a loaded cavity or the accelerating cavity may be used within its frequency range. The single drift tube $\lambda/4$ long at frequency f_k provides a shunt impedance of $R_{||} = 4Z_L$ with 3-dB bandwidth of $\pm\frac{1}{2}f_k$. Z_L is the characteristic TEM line impedance of the tube viewed as a coax within its outer chamber. Two drift tubes connected in series by a half-wave delay [7] give 4 times this impedance and about 45% of the bandwidth (see Fig. 7). This can match well the bandwidth required for an all-mode system operating at above Mf_0, the bunch rate. Broadband power amplifiers cost in the range of $100 to $200 per watt. For a more narrow bandwidth the resistive-loaded resonant cavity can make a very strong kicker. As with the transverse case, strong beam currents and parasitic resonances can create an electrode-heating problem and excess beam impedances. The kicker designer must compromise between kicker complexity and power cost.

3.3 Example Systems

A mode-by-mode system shown in Fig. 8 operates on the CERN PS Booster.[8] That proton synchrotron has 5 bunches in each of 4 stacked rings; the accelerating rf frequency at $5f_0$ sweeps from 3 to 8 MHz. At the 6th harmonic of f_0 , modes n=1 and n=4 are fed back and the filter response extends away from $6f_0$ far enough to include bunch-shape modes out to $\pm 3f_s$. The second channel covers modes 2 and 3 near $7f_0$. These filters track with the orbital frequency. The cavity response is wide enough to allow its use as a kicker.

A bunch-by-bunch feedback to cover all longitudinal modes is being constructed for the PEP-II B-factory,[9], in which 2.9-GHz signals at 238 MHz bunch rate are

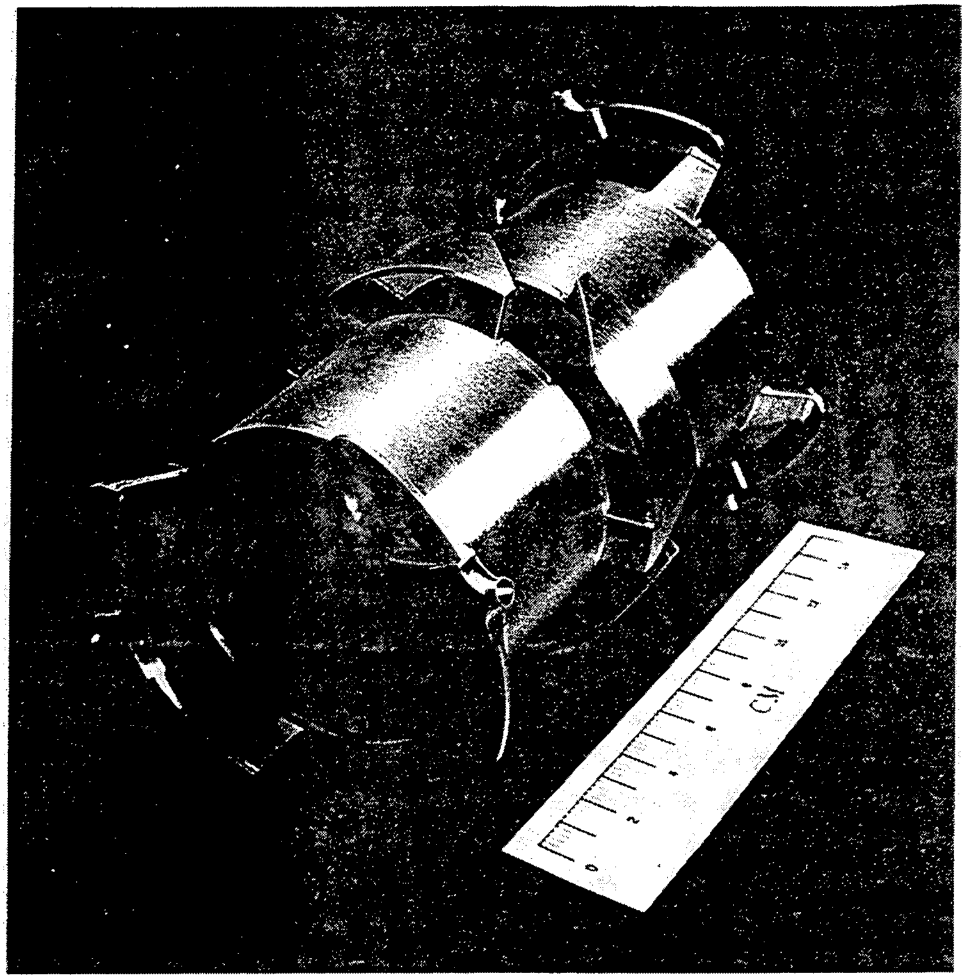

Figure 7: Two-in-series drift tubes for ALS feedback.

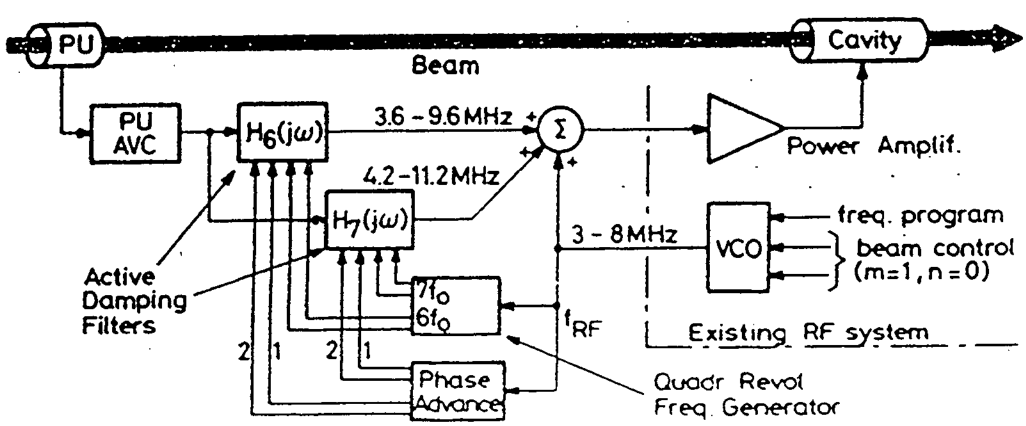

Figure 8: Mode-by-mode longitudinal feedback in CERN PSB.

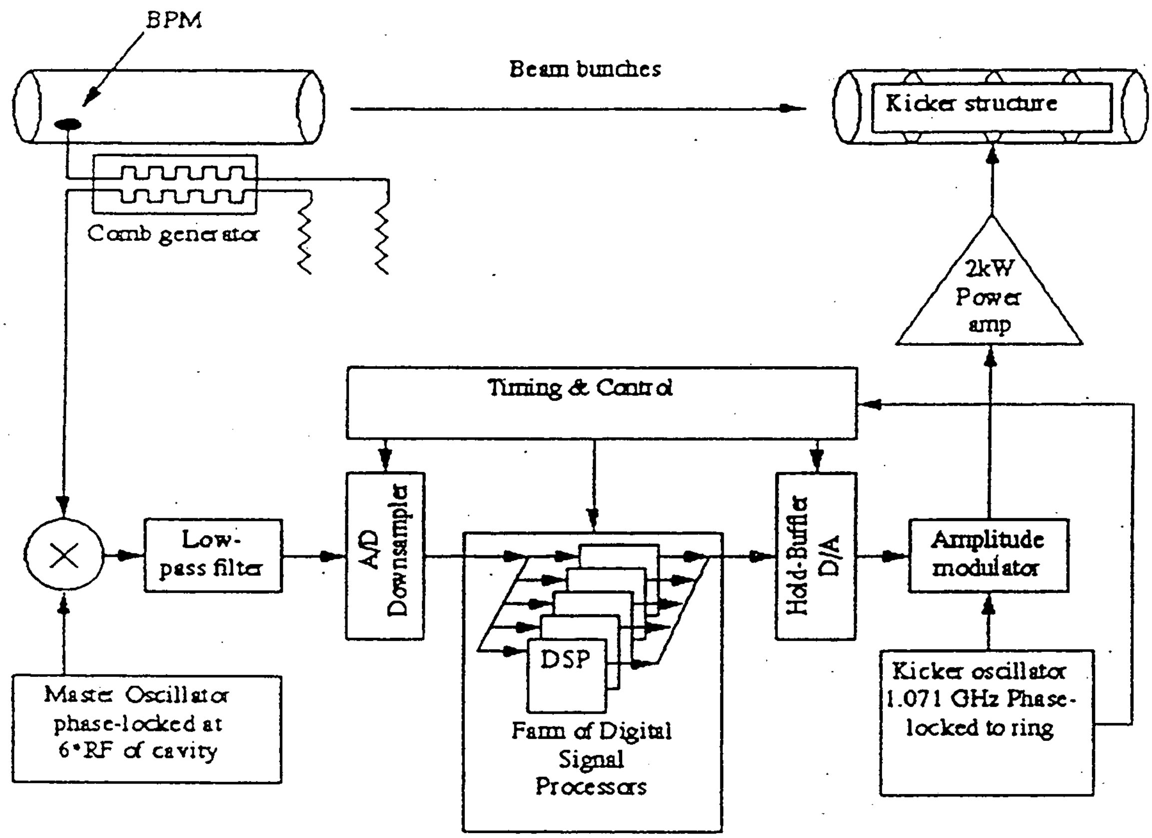

Figure 9: Diagram of PEP-II longitudinal feedback design.

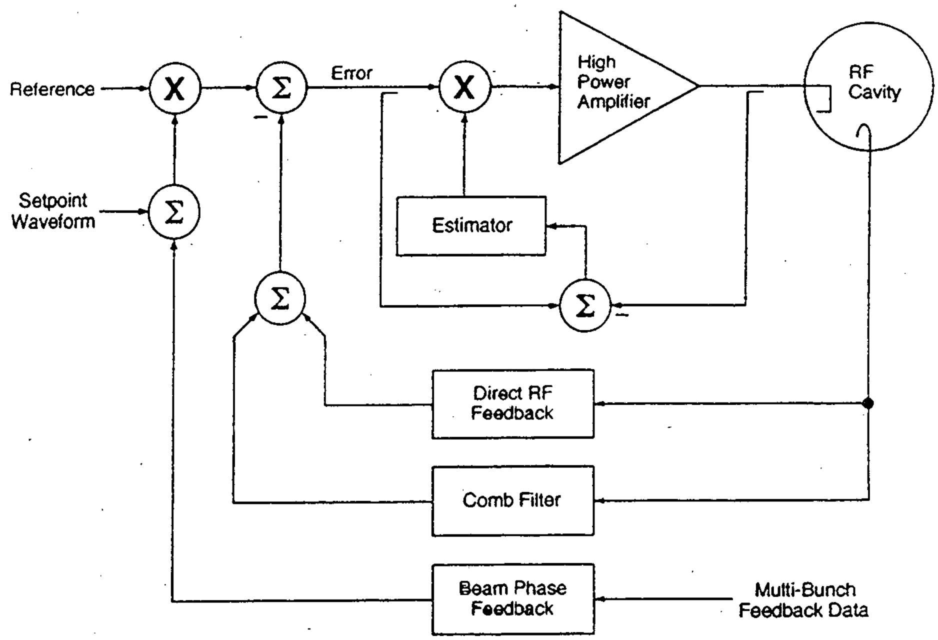

Figure 10: Block diagram of PEP-II rf system showing feedbacks to reduce cavity impedance.

phase-detected and digitized. About 20 turns pass during one phase oscillation; of the 20 signals-per-bunch, five are selected by the down sampler and sent to the farm of signal processors. There a 5-tap-per-oscillation FIR filter for each bunch generates the bunch phase signal, updated 5 times per synchrotron period. (These circuits are now in use at the LBL Advanced Light Source to control 328 bunches at 500 MHz rate.) The kickers operate over the band 0.95 to 1.07 GHz with a total power of 2 kW. There are four kickers, each being three drift tubes in series. Without reduction, the beam impedance of the fundamental mode of the accelerating cavities in PEP-II would drive a few c.b. modes at rates approximately 100 times stronger than that expected from higher-order cavity modes. The rf system with circuits [10] that provide the impedance reduction is diagrammed in Fig. 10. Prompt rf feedback reduces the impedance by a factor of 5 and feedback through dual-notch filters adds reduction at the c.b. sidebands to bring the growth rates under control with reasonable power and gain in the bunch feedback system. Table 2 lists some parameters of longitudinal c.b. feedback systems.

Table 2: Longitudinal Feedback Systems

a. Mode-by-mode

Machine	h	M	Kicker	Frequency	Power
PSB	5	5	RF cavity	3.6-11.2 MHz	-
PEP	2592	3+3	special cavity	860 MHz	55 kW
NSLS, VUV	9	9	stripline	400 MHz	100 kW
EPA	8	8	stripline	100 MHz	100 kW
Super-ACO	24	4	stripline	400 MHz	100 W
FNAL Booster	84	84	?	28 modes/filter	?

b. Bunch-by-bunch

Machine	h	M	Kicker	Frequency	Power
ISR	30	20	RF cavity	9.5 MHz	-
PEP	2592	3+3	special cavity	860 MHz	55 kW
SppS	4620	6+6	RF cavity	200 MHz	-
UVSOR	16	16	$\lambda/4$ Drift tube	90 MHz	100W
LEP	31320	4+4	RF cavity	352 MHz	-
ALS	328	328	2-in-series DT	1125 MHz	500 W
PEP-II (des.)	3492	1746	3-in-series DT	1012 MHz	2 kW

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