Title

Bunch-Motion Feedback forB-Factories

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Publication Date

1992-09-01

LBL-33359
UC-414

Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

Accelerator & Fusion Research Division

Presented at the Conference on B-Factories: The State of the Art in Accelerators, Detectors and Physics, Stanford, CA, April 6–10, 1992, and to be published in the Proceedings

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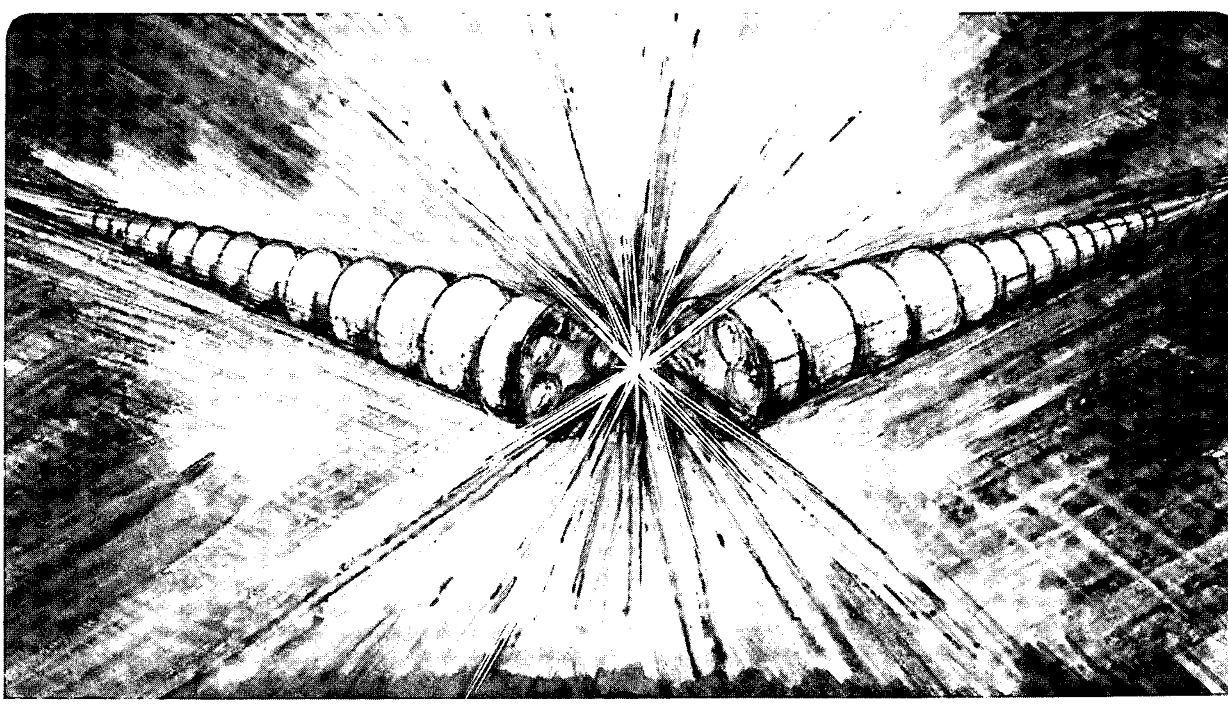
September 1992



Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

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LBL-33359
ESG-241
AP-95

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"B-Factories: The State of the Art in Accelerators, Detectors and Physics,"
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* This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

Bunch-Motion Feedback for B-Factories*

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INTRODUCTION

The colliding electron and positron beams in a B-factory must have average current of one ampere or more to produce the required luminosity. The high current interacts with structures in the beam tube to drive strong coupled-bunch (c.b.) instabilities. To suppress these instabilities requires negative feedback of the bunch motions. Beam impedances arising from strong rf cavity modes should first be reduced to make the required feedback damping rate practical and the cost economical. In what follows, control of transverse motions will be discussed first, then longitudinal. We shall use the parameters of the 3.1 GeV ring of PEP-II [1] to illustrate the general requirements.

TRANSVERSE C.B. MOTION FROM RESISTIVE WALL

While the wake field from the smooth wall of the beam tube is strong only at low frequencies, in a large diameter ring it can drive many c.b. modes. A beam tube of circular aperture with radius b has the transverse R-wall impedance at frequency ω given by

$$Z_\perp = (1+j)\,2\frac{\omega_o}{\omega}\frac{R^2}{b^3}R' \tag{1}$$

where

ω_o = orbit frequency
R = orbit circumference
R' = surface resistivity $\left(\frac{\omega\mu_o\rho}{2}\right)^{1/2}$

Except for increasing the tube aperture, little can be done to strongly reduce this impedance.

The beam tube of PEP-II has an oval aperture with 5 cm vertical height. For this geometry the vertical resistive impedance is

$$R_V = 1.41 \times 10^6 \sqrt{\frac{\omega_o}{\omega}} \text{ ohm/meter.} \tag{2}$$

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This drives most strongly the c.b. mode that appears at the frequency $\omega = (1-\Delta\nu)\,\omega_o = 0.36\,\omega_o$, where the impedance is 2.34×10^6 ohm/meter. To learn if this will produce instability in the presence of damping from synchrotron radiation at the rate

$$\frac{1}{T_R} = 0.027 \times 10^3 \text{ sec}^{-1} \tag{3}$$

we can calculate the c.b. growth rate using

$$\frac{1}{T_\perp} = \frac{I_o f_o}{2\beta\, E/e}\,\Sigma\,\beta_\perp R_\perp \tag{4}$$

in which the summation is over the driving or damping contributions of transverse resistive impedances at all frequencies where a given c.b. mode appears. One should use the value of $\beta_\perp$ at the azimuth where $R_\perp$ acts on the beam. For PEP-II we have

I_o = 2.14 amp. average current
$E/e = 3.1 \times 10^9$ volt
f_o = 136.6 kHz orbit frequency
$\beta_\perp$ = 9.7 meter (average)

giving, for this R-wall impedance,

$$\frac{1}{T_\perp} = 1.1 \times 10^3 \text{ sec}^{-1} \tag{5}$$

This greatly exceeds the synchrotron damping, so we have instability for this lowest mode and, one can calculate, also for about 200 other modes.

The large number of growing modes from this and other impedances suggests that we apply feedback that acts on each bunch in real time. In such a bunch-by-bunch feedback (Fig. 1) we sense the excursion Δx of each bunch, delay that signal one turn and deliver it to the same bunch as a transverse kick $\Delta V_\perp$. The corrective kick needed to just cancel a transverse impedance R_V is

$$\Delta V_\perp = I_o\,\Delta x\,R_V \tag{6}$$

For the strongest R-wall impedance in PEP-II, a mode amplitude Δx of 1 mm will require the kick

$$\Delta V_\perp = 5.0\,\text{kV/turn} \ . \qquad (7)$$

After an initial damping, we expect Δx to be much smaller than 1 mm. Therefore, the errors in injected beam will determine the required kick amplitude. Beam injected with errors will contain many c.b. modes, their amplitudes being roughly proportional to the product of injected charge and its excursion. Only the unstable modes need damping but the feedback will attempt to damp all bunch excursions. However, we can allow the excursions of some bunches to exceed the linear response capacity of the feedback as long as the unstable modes do not grow and accumulate as successive batches of beam are injected. We do this for economy of kicker power and for that reason also it is desirable to keep the product of charge-times-excursion small for any injected batch.

The proposal for control at injection into PEP-II is as follows. Each 1/60 second, inject 1/5 bunch charge with ~10 mm error. With the minimum gain of 5 kV per mm, this 1/5 x 10 mm calls for 10 kV/turn. The kicker is limited at 5 kV; this kick damps the error linearly from 2 mm to 1 mm, or further if the gain is set higher, then damps exponentially. Bunches other than the injected one are continually damped at full gain. After 1/60 sec all excursions are very small. This process has been simulated numerically for the longitudinal case; it is likely that the full 5 kV kick will not be needed for the transverse.

To feed back all possible c.b. modes, the electronics must have bandwidth of at least 1/2 the bunch rate (f_B = 238 MHz in PEP-II). The challenge is to handle the Δx-data at the bunch rate and delay it one turn, a few microseconds. Optical or digital delay systems can be used.

Electronic noise or digital least-count will enter as false bunch excursions x_N and drive betatron oscillations. This driven betatron motion x_{rms} is minimum for the gain of $2/f_o T_\perp$. At that gain, we have for PEP-II

$$x_{rms} \approx x_N \sqrt{\frac{2}{f_o T_\perp}} = 0.13\, x_N \ . \qquad (8)$$

This indicates that to keep residual oscillations less than the beam rms width does not require an unusually small input noise level.

BUNCH MOTION FROM TRANSVERSE MODES IN R.F. CAVITIES

Dipole modes in an rf cavity will occur up to the TE cutoff of the beam tube. In a cavity with 500 MHz fundamental we can expect three or more strong dipole modes. A typical mode may have $R/Q \approx 600\,\Omega$/m and in a copper cavity a Q-value of 60,000. Using Eq. 4, 10 such cavities in the ring would produce a very fast growth rate of ~ 10^5 Hz. Clearly we must damp these cavity modes to reduce the feedback task.

In PEP-II the plan is to reduce Q-values to $\leq$ 70 by attaching loaded waveguides to the copper cavity. For a ring with superconducting cavities, there are plans [2] to reach even lower Q by using large fluted bore tubes leading to resistive loads. For Q = 70 the growth rate becomes $1.8 \times 10^2\ \text{sec}^{-1}$ for the strongest mode. The broadened impedance curve of the damped resonance will make a few hundred c.b. modes unstable. These growth rates being much smaller than those from R-wall, they can be controlled by the feedback provided for the R-wall even if some resonances may overlap.

TRANSVERSE KICKERS AND THEIR DRIVERS

We may use a conventional opposed stripline pair, of length ℓ, to produce the required $\Delta V_\perp$ per turn. The power required is

$$P = (\Delta V_\perp)^2 / 2R_s \qquad (9)$$

with

$$R_s = 2Z_L \left(g_\perp \frac{\sin k\ell}{kb}\right)^2 \ . \qquad (10)$$

Example values are

Z_L = 50 ohm stripline impedance
$g_\perp \approx 1$ = electrode coverage factor
$b = \pm 25$ mm vertical half-gap
ℓ - 0.63 m - $\lambda/4$ at $\frac{1}{2} f_B$
$k = \omega/c$ over the range up to $\frac{1}{2} f_B$ = 119 MHz

From Eq. 10 we find that R_s is

63.5 kΩ at low frequency and
25.7 kΩ at 119 MHz.

For the R-wall modes, 5 kV/turn at low frequency requires a power of 200 watt. This power level at 119 MHz will give $\Delta V_\perp = 3.21$ kV which is adequate for the cavity-driven modes. While the nominal tune of PEP-II gives the lowest c.b. frequency $(1-\Delta\nu)\, f_0$ of 49 kHz, the driver should accommodate some tune variation. Therefore one would choose the driver range to be about 15 KHz-to-119 MHz and increase the power if needed. The driver cost is in the neighborhood of $100 per watt. Placement of the kicker where $\beta_\perp$ is large could reduce the power required.

The beam impedances of this kicker are not large and there are zeroes at all harmonics of f_B. At 115 MHz they are

longit. $Z_B = 25\ \Omega$
transv. $Z_B = 40\ k\Omega/m$.

LONGITUDINAL C.B. MOTIONS

The sources of destabilizing impedances for the phase motion are the same as for the transverse case but they have different relative importances. (1) The resistive-wall is not strong enough to produce growth. (2) Higher-order modes (HOM) of the cavity must be damped. (3) The fundamental (accelerating) mode can be a very strong effect and require special reduction.

A strong monopole HOM may have R/Q = 40 ohm and Q ≈ 36000 in a copper cavity. Ten such cavities would produce a growth rate of 10^5 sec^{-1}, which is large compared to the phase oscillation frequency f_s of about 7 KHz. If in PEP-II the Q could be reduced to about 17, the c.b. motion would be stabilized by radiation damping. While this degree of reduction is not inconceivable, the goal for PEP-II is to reduce Q to 70, which leaves a resonant HOM impedance of 28 kΩ to be opposed by feedback.

The net voltage causing growth of a c.b. mode interacting with resonators having impedances $R_{\parallel}$ at the c.b. mode frequencies f_{cb} is

$$\Delta V_{\parallel} = I_0 \Delta\phi \Sigma \frac{f_{cb}}{f_{rf}} R_{\parallel} \ . \qquad (11)$$

Here $\Delta\phi$ is the mode amplitude in phase relative to the rf frequency f_{rf}. The summation is over all + and - frequencies of the c.b. mode. For the 10 PEP-II cavities, the strong HOM is 28 kΩ at 760 MHz, which makes an effective impedance

$$R_{eff} = \frac{760}{476} 28{,}000 = 45\ k\Omega \qquad (12)$$

A mode amplitude of 0.03 radian (1/3 σ_L) inserted in Eq. 10 would call for a feedback kick of ~ 3 kV per turn to oppose this HOM assuming that no other resonances add to the sum for this c.b. mode.

For suppressing hundreds of modes, and other phase disturbances, the bunch-by-bunch feedback seems most appropriate. Starting from a pickup of bunch phase, a shift of 90° at the phase oscillation frequency f_s is needed to drive a kicker that acts on the energy of the bunch. Our example value of f_s is 7 kHz, or 20 turns per phase oscillation. For this it is best to use digital signal processing (3) with the phase of each bunch stored only every fourth or fifth turn. This then operates with a reduced input data rate but the processor can still generate a kick amplitude for each bunch every turn.

Beam injected with large errors in energy or phase can exceed the linear-range capability of the kicker driver, e.g. 3 kV/turn. A numerical simulation [3] of this behavior is shown in Fig. 2. A single bunch with initial error of 0.01 radian is injected; the reduction of its error (labeled $\phi(5)$) is shown in the upper graph. The bunch next downstream is most strongly driven by the wake field and its phase motion is shown in the lower graph, with expanded scale. In PEP-II the next injection, into a different bucket, would occur at 2,300 turns. It seems clear that the bunch motions are controlled and will not accumulate.

EXCITATION BY THE FUNDAMENTAL MODE

In rings of small radius, only the c.b. mode m=0 is strongly influenced by the impedance of the fundamental cavity mode. Other c.b. modes are separated by multiples of the orbital frequency, f_0. In a large-radius ring the small value of f_0 can place several of the c.b. modes that are near m=0 within the resonance response width of the cavity fundamental. Detuning of the resonant frequency to allow efficient power transfer to the beam as a load will then provide either strong excitation or damping of those modes.

This situation is sketched in Fig. 3; here the c.b. modes are shown where they fall on the detuned cavity impedance. The cavity resistive impedance is in the exciting sense where c.b. mode frequency is $nf_0 + f_s$ and damping for $nf_0 - f_s$. One can see that modes -1, -2, -3, etc are driven. The effect is reduced by having higher voltage and larger loaded Q, as might be the case in superconducting cavities operating with higher stored energy, but the problem is not removed in a ring with f_0 on the order of 100 KHz.

To combat this destabilizing effect, we wish to reduce the apparent impedance of the cavity in response to beam current; this corresponds to making it appear more like a voltage source. Fast feedback of cavity rf voltage to and through the driving klystron can be used but the degree of reduction is limited to about a factor of ten by delay in the feedback loop through the klystron and other circuits. Further reduction can be realized by feedback through notch filters that act only in the vicinity of the c.b. mode frequencies.

After those modifications of the cavity response, residual instability in modes within the fundamental response can be suppressed by the bunch feedback and by using the klystron-cavity system as a strong supplemental kicker applying corrective signals available from the bunch-by-bunch phase feedback system.

LONGITUDINAL KICKERS

The cost of wide-band (1/2 f_B) power amplifiers to drive the kickers can be significant. One must also consider the number and complexity of kicker units, overall length, and beam impedance. As a reference example, use N kicker units each consisting of a drift tube with 25-ohm line impedance. For PEP-II parameters, the lowest frequency band is < 7 KHz-to-119 MHz. This is an awkward range for a power amplifier, hence we can shift upward by 8 x 119 Hz to the range 952-to-1071 MHz. Here the length of a $\lambda/4$ drift tube is 7.4 cm and the cost of power is about $140 per watt. The shunt impedance of a unit is 100 ohm. To provide 3 kV/turn using, for example, 8 units the power required is

$$P = \frac{1}{8}\frac{(3000)^2}{(2)(100)} = 5.6\,\text{kW} \qquad (13)$$

and the amplifiers cost about 0.8 M$. The low-frequency beam impedance is 200 ohm over a band of about 1 GHz.

A kicker having higher shunt impedance and more narrow bandwidth can be made by connecting $\lambda/4$-drift tubes in series by $\lambda/2$-delay lines. Such a structure with two tubes in series is shown in Fig. 4. A four-in-series unit will have a shunt impedance of 1600 ohm and 3 dB frequency band of 900-to-1120 MHz. Two of these units will provide the 3 kV/turn with one-quarter the power of the 8 single units, 1.4 kW costing 0.2 M$. The area under the beam-impedance curve is the same as for the eight separate drift tubes, now being 800 ohms over about 1/4 GHz.

SUMMARY

With many bunches and high current in the B-factory many hundreds of coupled-bunch modes will be unstable. To suppress the growth of all modes requires feedback systems with bandwidth at least one-half the bunch rate, a few hundred MHz. Reduction of the impedances of rf cavity modes is necessary to make feedback practical, and in the longitudinal case to make it feasible.

Real-time bunch-by-bunch feedback can stabilize the bunch motions and damp injection errors and other disturbances. Digital processors can provide the required data rate and the needed time-delays and phase shift. For economy it is desirable to limit the kicker power and operate in the non-linear range in response to the large errors in injected beam. Schemes that inject beam batches with a small product of charge x error are most readily controllable.

For the transverse motions, the resistive-wall impedance produces the fastest growth rates after cavity modes are reduced by a factor of several hundred. Longitudinal motions have an additional excitation from the shoulders of the r.f. fundamental mode. This must be reduced with fast rf feedback through the klystron and supplemental gain in the bunch-motion feedback for low-frequency modes. Some special design of the kickers for the broad-band feedback will save on system costs.

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[2] K. Berkelman, et al., "CESR-B: Conceptual Design for a B Factory Based on CESR," CLNS 91-1050, January 1991.

[3] D. Briggs, et al., "Computer Modeling of Bunch-by-Bunch Feedback for the SLAC B-Factory Design," 1991 IEEE Particle Accelerator Conf. p. 1407, May 1991.

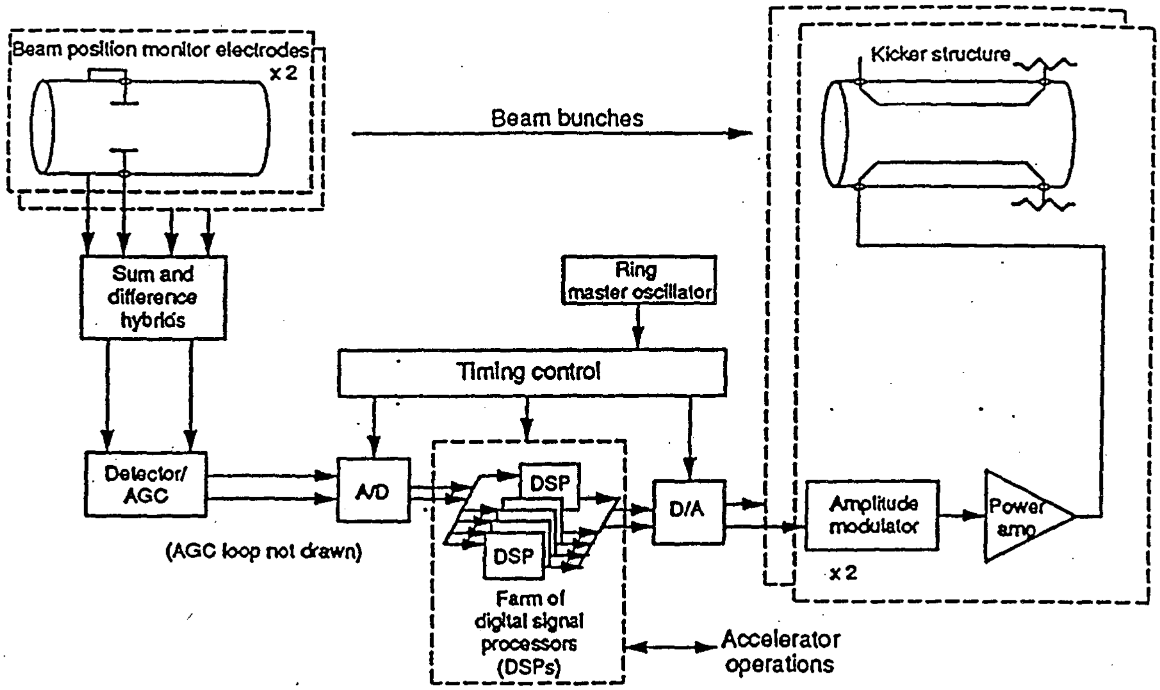

Fig. 1 Block diagram of the transverse feedback system.

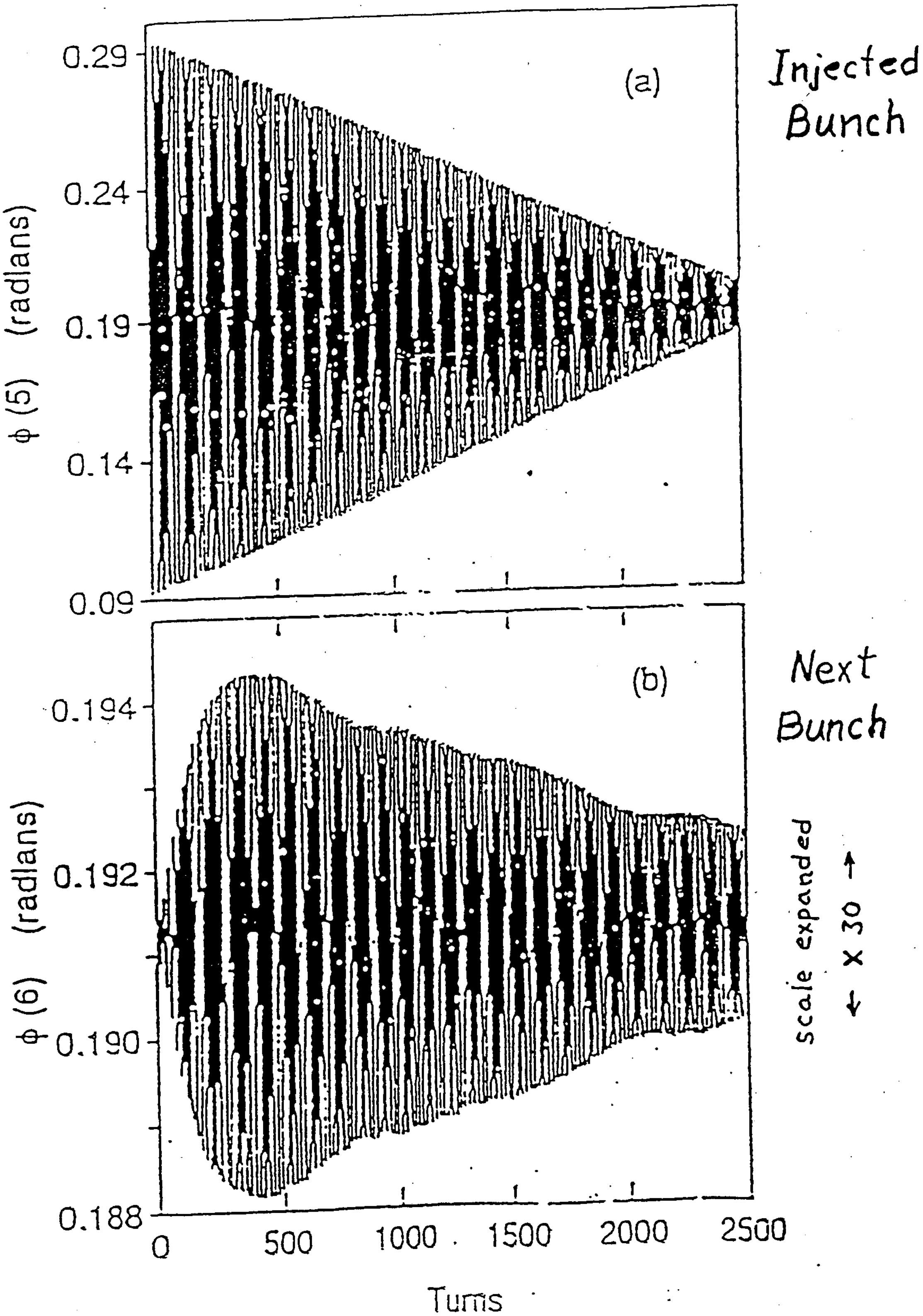

Fig. 2 Simulated damping at injection.

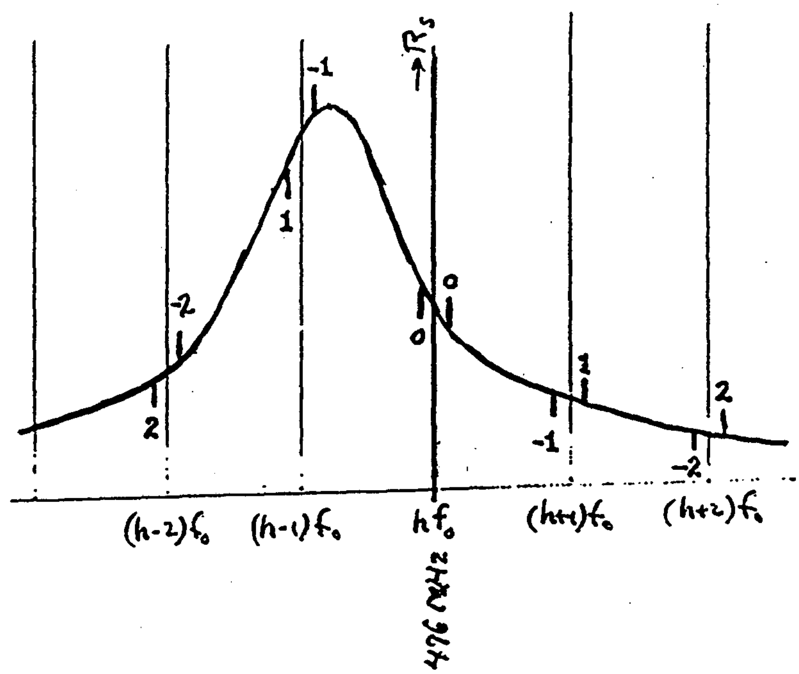

Fig. 3 Driving impedances for coupled-bunch modes near the rf acceleratig frequency hf_0.

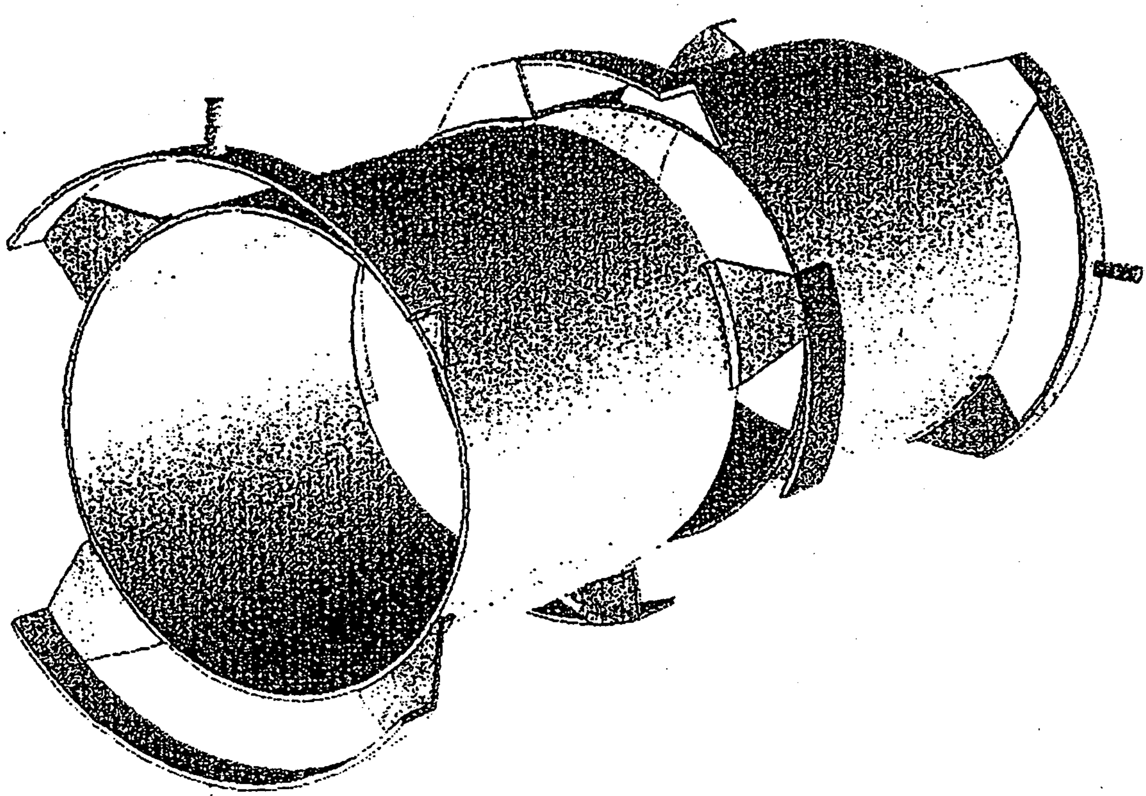

Fig. 4 Two-in-series kicker electrode.

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