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**COLLECTIVE EFFECTS IN THE PEP-II B-FACTORY\***

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# COLLECTIVE EFFECTS IN THE PEP-II B-FACTORY\*

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## Abstract

The expected major collective effects in the PEP-II B-factory are discussed and thresholds presented. Broadband and narrow band impedance values are reviewed. Instabilities not related to impedance are discussed.

## Introduction

A circulating charged particle beam interacts with its surroundings through electromagnetic fields, inducing image currents on vacuum chamber walls, which in turn give rise to time-varying electromagnetic fields which act back on the beam. These fields can cause instabilities and degrade beam quality. This interaction is often characterized by the beam impedance of a device or structure, or in time domain the wakefield. In devices such as bellows shields, vacuum valves, RF cavities, kickers, etc. the electromagnetic interaction may be particularly strong, and there is an active program to quantify and minimize all impedances in PEP-II [1]. In addition, we are also concerned with non impedance related effects such as ion-driven instabilities of the electron beam in the high energy ring (HER), and electron-plasma driven instabilities of the positron beam in the low energy ring (LER).

Table 1 lists some relevant parameters for the PEP-II B-factory storage rings. The low energy and high current in the LER generally produce the most demanding conditions in terms of collective effects in PEP-II. Although the nominal maximum current is 2.14 A, components are being designed with a 3 A current specification.

	Low energy ring	High energy ring
Energy (GeV)	3.1	9
Total current (A)	2.14	0.99
Bunch length rms (cm)	1	1
Current per bunch (mA)	1.3	0.6
Peak current (A)	113	53
Momentum compaction	0.00124	0.0024
Momentum spread	7.74E-04	6.00E-04
Synchrotron tune	0.033	0.051
Energy damping time (ms)	26	18
Horizontal damping time (ms)	52	37
Radiation loss per turn (MV)	0.866	3.58
RF voltage (MV)	5.1	18.3

Table 1. PEP-II parameters.

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## Single-bunch instabilities

Most important of the single-bunch instabilities are the longitudinal microwave instability (turbulent bunch lengthening) and the transverse mode coupling instability. These instabilities are driven by the broadband beam impedance. For the longitudinal microwave instability the threshold peak current is given by:

$$I_p = \frac{2\pi |\eta| \left(\frac{E}{e}\right) (\beta\sigma_p)^2}{\left|\frac{Z_{||}}{n}\right|_{\text{eff}}}$$

where  $|Z_{||}/n|_{\text{eff}}$  is the magnitude of the effective longitudinal broadband impedance experienced by a single bunch. For the LER, the nominal peak current is 113 A and stability requires  $|Z_{||}/n|_{\text{eff}} \leq 0.13 \Omega$ . For the HER, peak current is 53 A, and stability requires  $|Z_{||}/n|_{\text{eff}} \leq 0.9 \Omega$ .

In order to estimate  $|Z_{||}/n|_{\text{eff}}$  we generate  $Z/n(n)$  from the impedance budget. The resistive-wall impedance dominates at (very) low frequencies and contributes little to the total broadband impedance. RF cavity higher-order modes (HOM's) below the beam pipe cut-off frequency provide sharp resonances ( $Q > 30$ ) described by Lorentzian curves. Cavity modes above cut-off are modeled as  $Q=1$  resonator centered at the beam pipe cut-off frequency and with a loss parameter determined by a time-domain computation (ABCI), with the contributions from modes below cut-off subtracted. Vacuum chamber components such as bellows shields, valves, and kickers are modeled as a  $Q=1$  resonator with loss parameter and low frequency inductance determined from impedance calculations for these components [1]. Figure 1 shows this impedance as a function of harmonic number  $n$ .

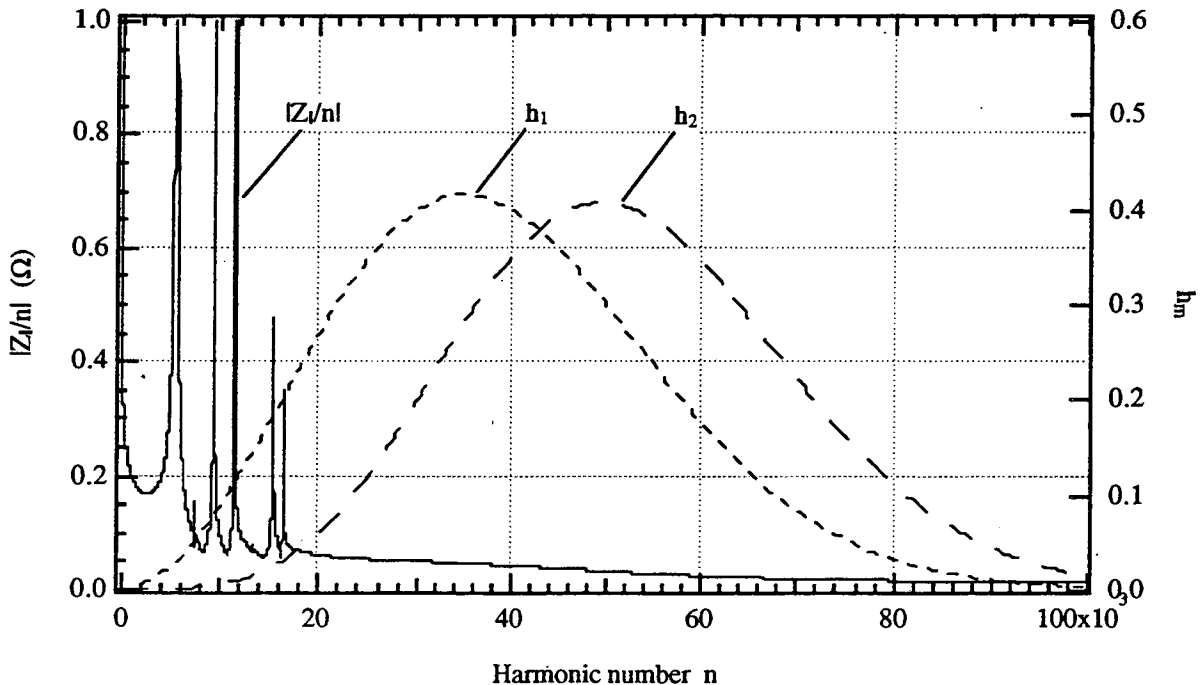


Figure 1. LER beam impedance spectrum.

Only frequencies with wavelengths of the order of a bunch length are effective in creating turbulence, and we may estimate the effective impedance as the weighted average of the impedance over the power spectra of the mode(s) involved in the instability (although we may not know which modes are involved).

$$\frac{|Z_{||}|}{n}_{\text{eff}} = \frac{\int \frac{|Z_{||}|}{n} h_m^2 dn}{\int h_m^2 dn}$$

where  $h_m$  is given by

$$h_m(y) = \frac{1}{\Gamma(m + \frac{1}{2})} y^{2m} e^{-y^2}$$

and  $y = \omega \sigma_t$ . For  $h_1$ ,  $|Z_{||}|/n_{\text{eff}} = 0.047 \Omega$  (for the LER). As a more conservative estimate we take  $|Z_{||}|/n_{\text{eff}}$  to be the impedance  $|Z_{||}|/n$  at beam-pipe cut-off frequency (2.4 GHz in the straight sections,  $n = 17 \times 10^3$ ). Then for the LER  $|Z_{||}|/n_{\text{eff}} = 0.07 \Omega$ , and for the HER  $|Z_{||}|/n_{\text{eff}} = 0.12 \Omega$ .

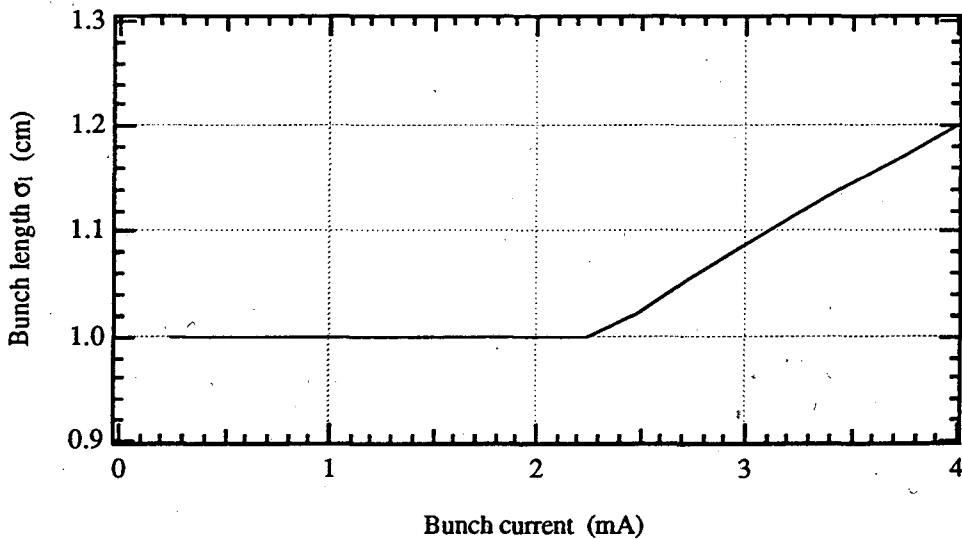


Figure 2. LER bunch lengthening characteristics for  $|Z_{||}|/n_{\text{eff}} = 0.07 \Omega$ .

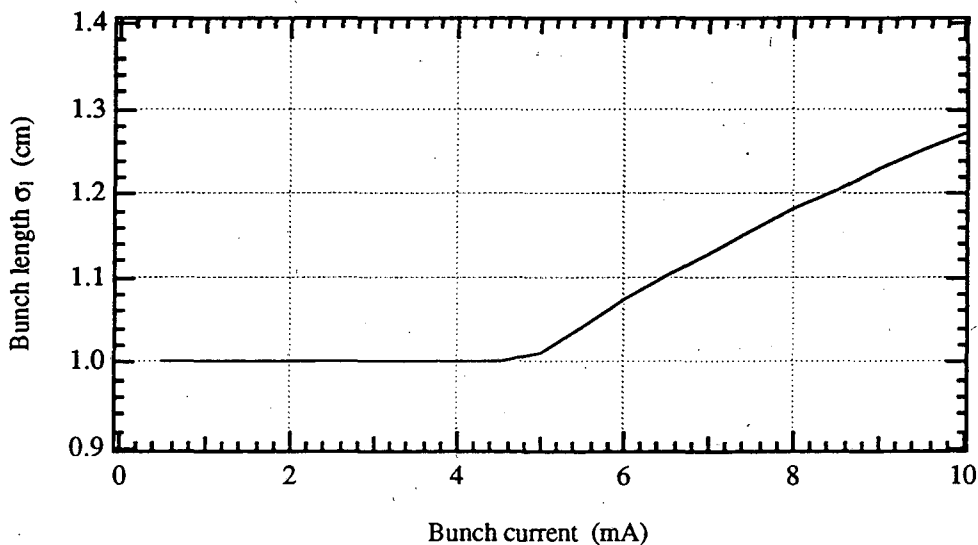


Figure 3. HER bunch lengthening characteristics for  $|Z_{||}|/n_{\text{eff}} = 0.12 \Omega$ .

Using these impedance values the threshold peak currents for the onset of the microwave instability are 207 A in the LER and 407 A in the HER, and we operate comfortably below the instability threshold at nominal currents. Figures 2 and 3 show bunch length as a function of current per bunch in the LER and HER respectively.

Note that the broadband impedance may also be estimated from the total loss parameter. Reference [1] gives 3.25 V/pC from the vacuum chamber components, and 0.515 V/pC from each RF cavity. For the LER the total loss factor is then 7.37 V/pC, and we may generate a  $Q=1$  resonance at the beam pipe cut-off frequency with the same loss factor to model the broadband impedance. This gives  $|Z_{||}/n|_{\text{eff}} = 0.03 \Omega$ .

Figure 4 shows the variation of threshold current as a function of RF voltage in the LER. Figure 5 shows the threshold current as a function of energy for the LER (at nominal RF voltage).

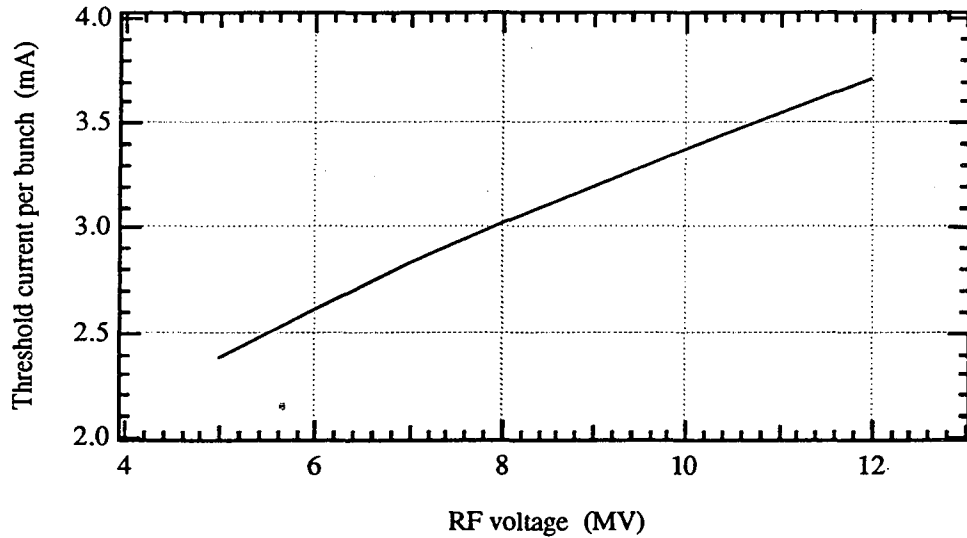


Figure 4. LER microwave instability threshold current per bunch as a function of RF voltage.

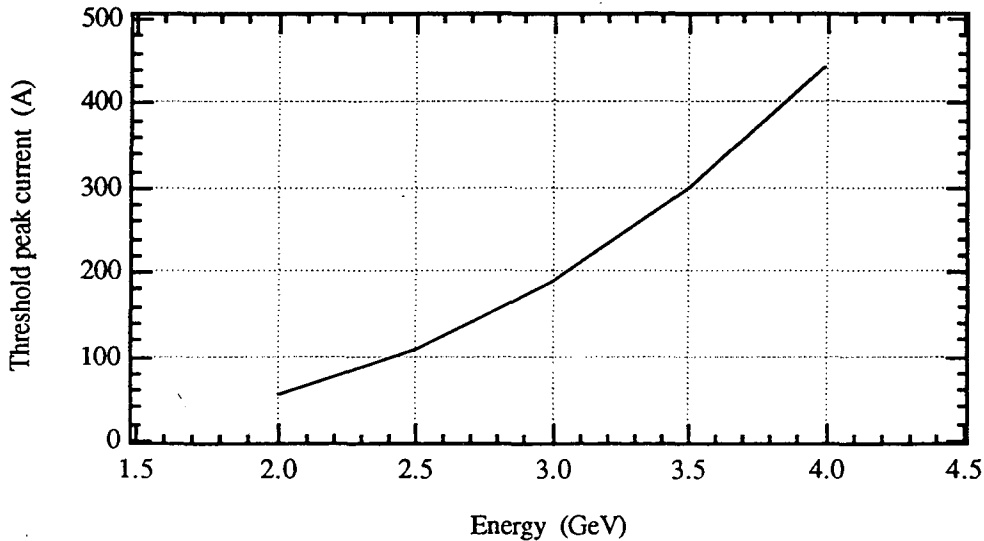


Figure 5. LER microwave instability threshold peak current as a function of beam energy.



Potential well distortion to achieve a 10 % bunch lengthening requires an inductive impedance of 225 nH. We estimate an inductive impedance of 80 nH, well below this limit, and the bunch remains Gaussian and undistorted at nominal currents [1].

The threshold current per bunch for the transverse mode coupling instability is given by:

$$I_b = \frac{4 \left(\frac{E}{e}\right) v_s}{\langle \text{Im}(Z_{\perp}) \beta_{\perp} \rangle R} \frac{4\sqrt{\pi}}{3} \sigma_1$$

where  $Z_{\perp}$  is the effective broadband transverse impedance. We estimate this transverse impedance as a broadband resonator centered at the beam pipe cut-off frequency, related to the longitudinal broad-band impedance:

$$Z_{\perp} = \frac{|Z_{\parallel}|}{n_{\text{eff}}} \left(\frac{2R}{b^2}\right)$$

where  $R$  is the machine radius and  $b$  the average vacuum chamber radius (or half-height). For the LER  $Z_{\perp}^{\text{vertical}} = 50 \text{ k}\Omega/\text{m}$ , and for the HER  $Z_{\perp}^{\text{vertical}} = 90 \text{ k}\Omega/\text{m}$ . MOSES predicts threshold current per bunch of 50 mA in the LER, and 140 mA in the HER, including the effects of bunch lengthening. Figures 6 and 7 show the transverse mode frequencies as a function of current for the LER and HER.

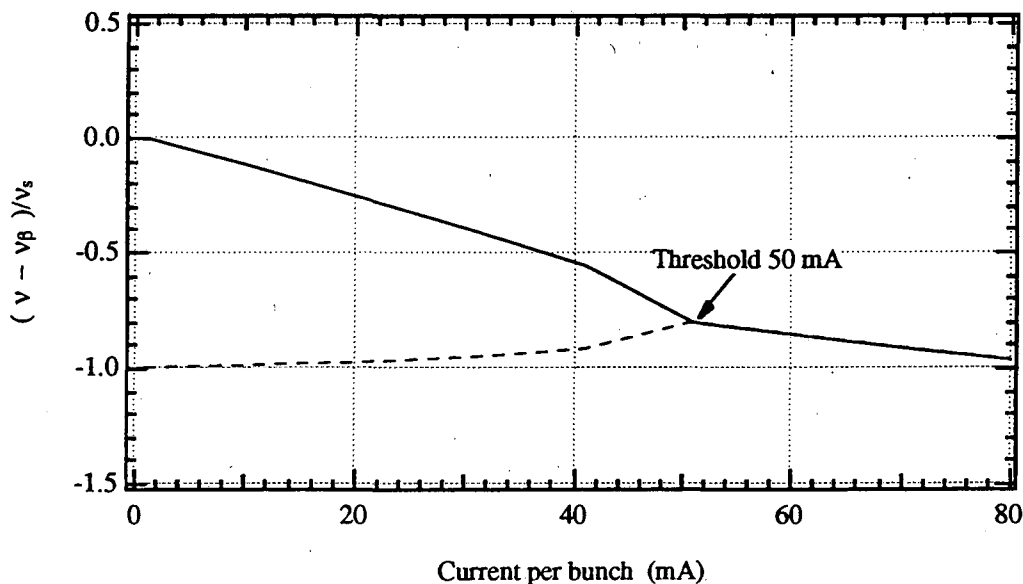


Figure 6. LER transverse mode coupling,  $Z_{\perp}^{\text{vertical}} = 50 \text{ k}\Omega/\text{m}$ .

Since scaling from the longitudinal broadband impedance may prove unreliable, we also calculate the mode coupling threshold for the extreme case of  $Z_{\perp} = 1 \text{ M}\Omega/\text{m}$ . Again using MOSES, we predict a threshold current of 2.5 mA per bunch, still comfortably below our nominal current per bunch of 1.3 mA.

This instability mechanism also contributes to the growth of the  $m=1$  coupled bunch modes, as discussed later.

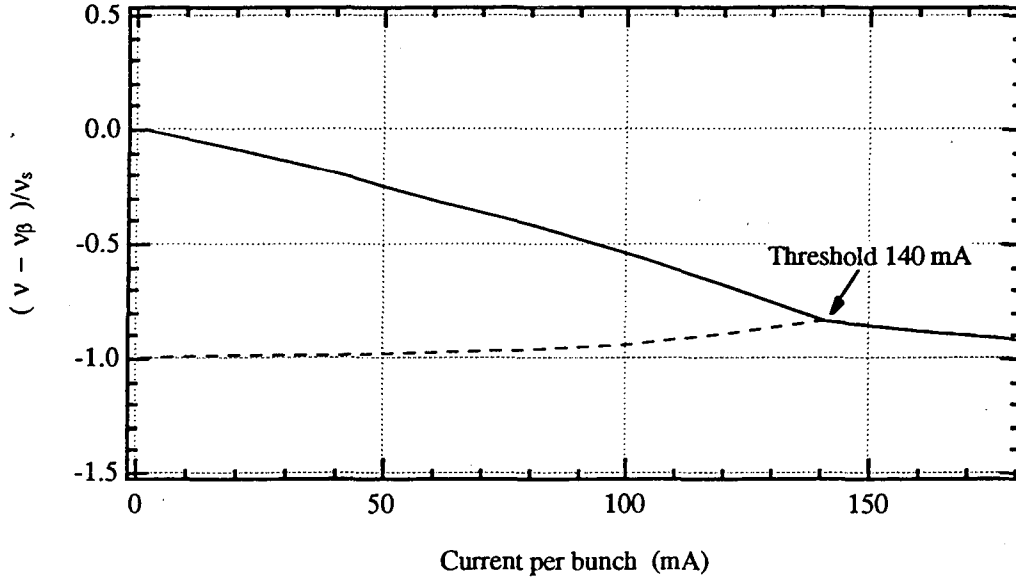


Figure 7. HER transverse mode coupling,  $Z_{\perp}^{\text{vertical}} = 90 \text{ k}\Omega/\text{m}$ .

#### Coupled-bunch instabilities

Longitudinal coupled-bunch motion is dominated by cavity HOM's. Transverse coupled-bunch motion is also strongly influenced by the resistive wall impedance. For rigid bunch motion, the longitudinal frequency shift is given by:

$$\Delta\omega = j \frac{I_{\text{rf}}}{2E} \alpha_p \frac{f_0}{f_s} Z_{\text{eff}}^{\text{long.}}$$

where

$$Z_{\text{eff}}^{\text{long.}} = \sum_{p=-\infty}^{p=+\infty} \frac{\omega_p}{\omega_{\text{rf}}} e^{-(\omega_p \sigma_{\tau})^2} Z^{\text{long.}}$$

and  $\omega_p = (pM + n + Q_s)\omega_0$  is the coupled bunch mode frequency,  $Z^{\text{long.}}$  is the HOM impedance. For transverse coupled bunch motion we have:

$$\Delta\omega = -j \frac{I f_0}{2E} \beta_{x,y} Z_{\text{eff}}^{\text{trans.}}$$

where

$$Z_{\text{eff}}^{\text{trans.}} = \sum_{p=-\infty}^{p=+\infty} e^{-(\omega_p \sigma_{\tau})^2} Z^{\text{trans.}}$$

and  $Z^{\text{trans.}}$  includes the resonant HOM impedance and the resistive wall impedance, the latter being given by

$$Z_{\text{trans. res. wall}} = A(1+j) \frac{cL}{\pi b^3} \sqrt{\frac{\mu_0 \rho}{2}} \frac{1}{\sqrt{\omega}}$$

where  $\omega_p = (pM + n + Q_{x,y})\omega_0$  is the coupled bunch mode frequency, and A is a factor that depends on the vacuum chamber geometry.

For RF cavities with *undamped* HOM resonances, the fastest longitudinal mode growth times would be 7  $\mu\text{s}$  in the LER, and 12  $\mu\text{s}$  in the HER. Note that this is substantially faster than the synchrotron period of 220  $\mu\text{s}$  in the LER, and 143  $\mu\text{s}$  in the HER. The fastest transverse mode growth times from HOM's are 30  $\mu\text{s}$  in the LER, and 45  $\mu\text{s}$  in the HER. The cavity fundamental mode also drives coupled bunch instabilities, as will be discussed later.

Clearly, damping of cavity HOM's is essential to reduce the growth rates to levels at which reasonable feedback systems can maintain control. In PEP-II this is achieved by damping-waveguides connected to the cavity body, resulting in shunt impedance reduction of up to three orders of magnitude [2]. Figures 8 and 9 show the per cavity impedance of HOM's below beam pipe cut-off frequency, with damping waveguides and without the damping waveguides, as measured on a low power test cavity. Schemes to provide additional damping of the strongest modes, through the use of tuned antennas and through the high power feeder coupling aperture, are being developed.

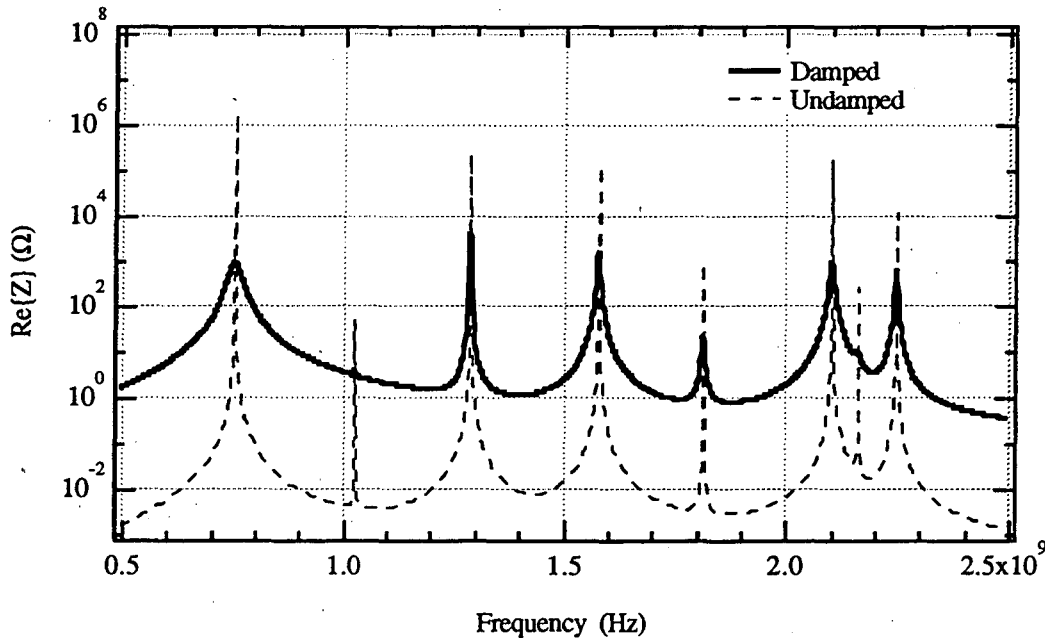


Figure 8. Monopole HOM impedance, with and without damping waveguides.

Fastest longitudinal coupled-bunch growth times from damped cavity HOM's are 1 ms in the LER, and 2 ms in the HER. This is to be compared with the LER energy damping time of 26 ms and HER energy damping time of 18 ms. In the transverse direction the fastest growth times are 0.5 ms in the LER, and 1.0 ms in the HER. LER transverse damping time is 52 ms, and HER damping time 37 ms. Figures 10 and 11 show the effective impedance, and growth rates (at 3 A total current) for the longitudinal and transverse modes in the LER [3]. All modes have been aliased into a 119 MHz frequency band, which incorporates all coupled bunch modes for the 4.2 ns bunch spacing. Note the 1/f response of the resistive wall impedance at low frequencies in the transverse impedance.

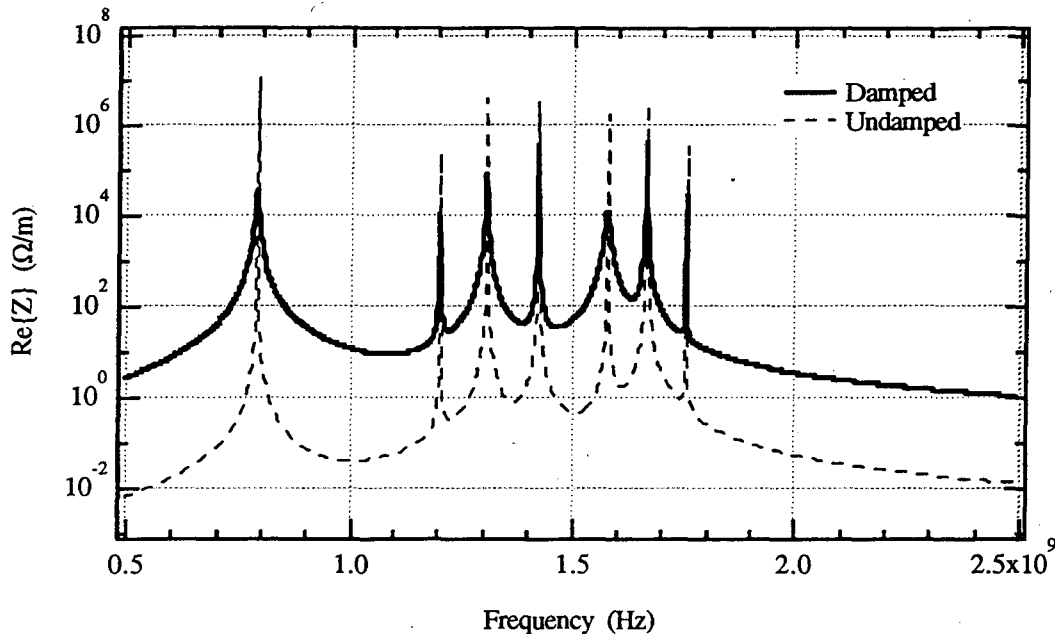


Figure 9. Dipole HOM impedance, with and without damping waveguides.

Longitudinal and transverse feedback systems are essential to maintain stability against these coupled-bunch oscillations. Bunch-by-bunch systems are being designed, with sufficient power to control coupled-bunch modes excited by transients and sufficient gain to control the fastest growing modes excited by noise [4,5,6].

In addition to the rigid-bunch modes, transverse multibunch head-tail modes ( $m=1$ ) may also be excited. Coupling between the single bunch (driven by the broadband impedance) and multi-bunch (driven by narrow-band HOM impedance) effects may substantially increase the growth rates of these modes at high currents [7]. Since the transverse coupled-bunch feedback systems operate on the beam moment signal ( $I_{\text{bunch}}\Delta_{x,y}$ ) and are not sensitive to within-bunch distribution, they are not effective in suppressing this instability. Additional damping schemes to further suppress the two cavity HOM's driving this instability are being developed.

Longitudinal coupled-bunch motion may also be driven by the fundamental mode of the RF cavities, where large detuning of cavities (of the order of a revolution frequency) is required to accommodate beam loading at high currents. The fundamental mode impedance then covers longitudinal coupled-bunch mode frequencies, and provides a substantial driving impedance for many modes. Feedback systems operating around the RF power systems to reduce the fundamental mode impedance at the coupled-bunch mode frequencies are required, and are being designed and tested [8]. The broadband coupled-bunch longitudinal feedback system also feeds into the RF system drive to allow further suppression of the modes driven by the fundamental.

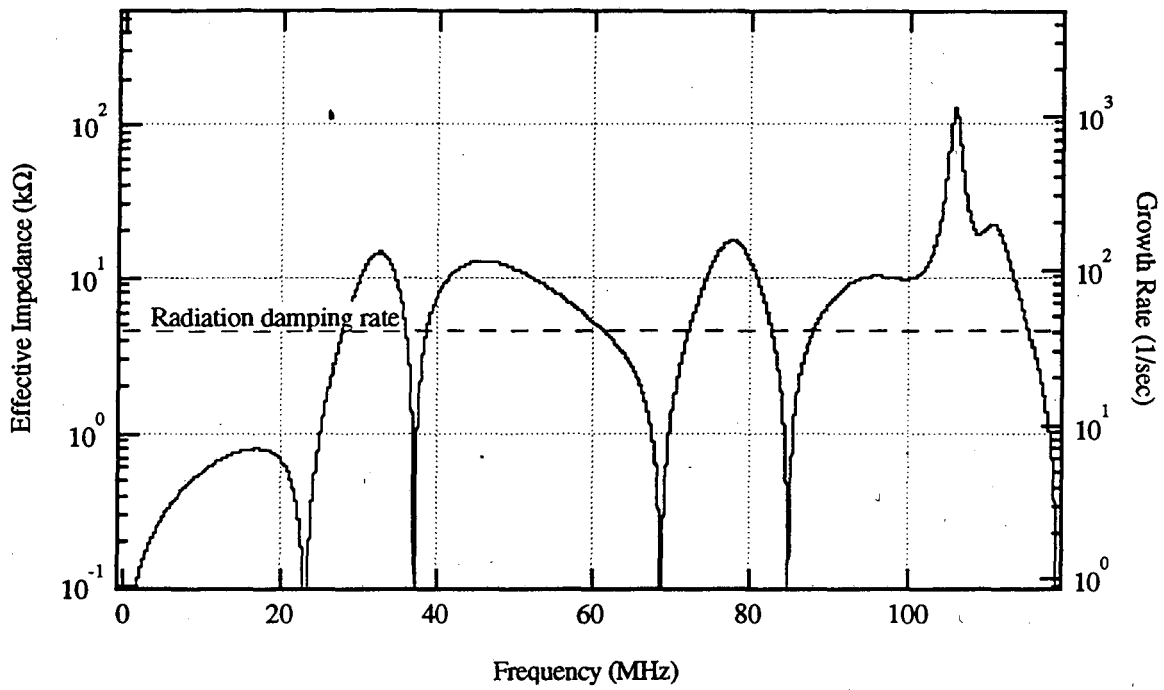


Figure 10. LER effective longitudinal impedance and growth rates, 8 cavities, 3A.

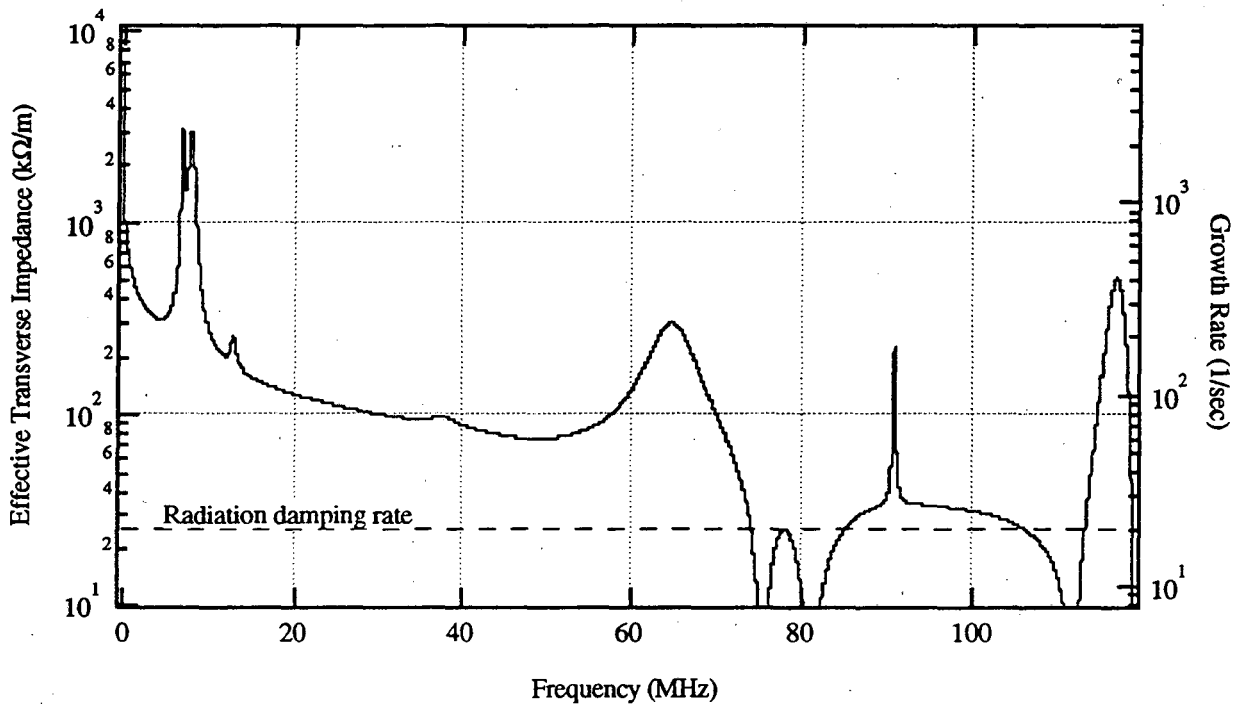


Figure 11. LER effective transverse (vertical) impedance and growth rates, 8 cavities, 3A.

## Non-impedance related instabilities

Effects due to free electrons or ions in the storage rings may give rise to instabilities with appreciable growth rates, which are currently being investigated.

A multipactor resonance instability may occur in the LER if the free electrons in the vacuum chamber are accelerated across the aperture due to the potential of the beam, and strike the wall with enough energy to create more electrons at the surface. If the time for passage of electrons from one side of the vacuum chamber to the other is equal to the time interval between the positron bunches in the LER, and the accelerating field of the bunch is sufficient to provide the electrons with enough energy to produce secondaries at the collision with the wall, a resonance effect is created. For the LER conditions in PEP-II, the current is safely below this threshold and the instability is avoided [9].

Photo-electrons emitted from the vacuum chamber surface in the positron ring (LER) are attracted to the beam and accumulate in the beam chamber. The density of the electron cloud increases along the bunch train as photoelectrons and secondaries are produced. A transverse displacement of the positron beam then induces a wakefield in the electron plasma, which may persist for several bunch passage times and couple the transverse motion to following bunches, with growth times perhaps of the order of milliseconds or less [10]. Simulations and analytic methods are being developed to further analyze this effect. These will include accurate modeling of the accelerating electric and magnetic fields, energy spread of the photoelectrons, reduction of secondary emission by use of low emissivity surface coatings, etc.

In the HER an instability known as the fast ion instability may give rise to transverse coupled bunch motion with growth times of tens of microseconds [11]. The train of electron bunches causes an increasing density of ions as the residual gas is ionized. Although this ion cloud may be cleared by leaving a gap in the bunch train to allow ions to collide with the vacuum chamber walls and re-combine, the ion density may be sufficient to couple transverse motion between bunches in the train. This coupling will be enhanced at the ion resonance frequency, which varies around the lattice as the potential of the electron beam changes with the beam size. Thus the instability may be characterized by low frequency beam modes correlating with the spread in ion frequencies. Simulations and analytic studies are being developed to study the instability. Experiments performed at synchrotron radiation sources have not been conclusive in demonstrating the effect, however more experiments are planned.

## Acknowledgements

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