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Study of Collective Effects

for the

PEP Low-Emittance Optics*

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Abstract

Experimental studies have been performed on the PEP storage ring run at 7.1 GeV in the low-emittance mode. The motivation for this work is to explore the capability of PEP as a dedicated synchrotron radiation source. The long straight sections and low emittance available at PEP make its use for this purpose very attractive, and would produce a source of very high brightness x-ray beams for the scientific community. During the studies, single-bunch current limitations were measured as a function of RF voltage. Thresholds were in the range of 1-2 mA per bunch, which is lower than expected based upon transverse impedance estimates from the PEP collider optics. An increase in threshold current by about 50% was realized by modifying the optics to reduce the magnitude of the horizontal beta functions in the straight sections and at the RF locations. The reason for the lower than expected thresholds has not been resolved. To permit its effective use as a synchrotron radiation source, a beam current of 50-100 mA is desired, which will require that PEP be run in the multibunch mode. Our goal in this study was to investigate the multibunch operating mode to ascertain that reasonable beam intensities were possible. By utilizing many low intensity (0.1-0.25 mA) bunches, stable and reproducible currents of 15-20 mA were achieved. In an attempt to improve this value, one of the idle RF stations was operated in a tune-splitting mode, with only partial success. By adjusting the tuner positions of the unused RF stations, up to 33 mA was ultimately stored, albeit with some evidence for instability. Possible approaches to improving the multibunch stability are discussed.

1. INTRODUCTION

In this paper we describe the results of a series of accelerator physics studies of the PEP storage ring at the Stanford Linear Accelerator Center (SLAC). PEP is an electron-positron collider that operates primarily for high-energy physics. However, its unique properties—described below—make PEP of great interest to the synchrotron radiation community as well.

The properties of PEP that make it especially attractive as a synchrotron radiation source are:

- High electron energy (up to 16 GeV with presently installed RF power)
- Large circumference (2200 m)
- Long straight sections (115 m)
- Highly flexible lattice
- Low dipole magnet fields (0.32 T at 16 GeV)

These features are unique among U.S. accelerators and they offer immense present capability and future potential as a low-emittance, high-brightness, x-ray synchrotron radiation source. In particular, the long straight sections could be utilized for the production of copious undulator radiation.

Two beam lines are now operational in PEP, each employing a 2-m permanent magnet undulator. In parasitic operation at 14.5 GeV, these undulators produce photon beams whose brightness (in the spectral region above 10 keV) is 10 times that of any other source. In recent tests with dedicated synchrotron radiation (low-emittance) optics, even higher brightness—estimated to be 1.5×10^{17} photons/(s·mm^2·mrad^2·0.1% bandwidth)—was achieved.

Optics for such a low-emittance mode were developed—and briefly tested in March 1986—by Brown *et al.*[1] The predicted emittance in the new optics, $\varepsilon_x = 8.3 \times 10^{-9}\ \pi$ m·rad at 8 GeV, is about a factor of three lower than would be obtained from the normal collider optics at the same energy. This value was roughly confirmed in the experiment described in Ref. 1 through direct measurements with the x-ray beam from the undulator, which gave an upper limit to the beam emittance of 12 x 10^{-9} π m·rad—the lowest emittance that had ever been measured in a synchrotron radiation source.

Based on these encouraging results, additional calculational work has been undertaken to explore ways of extending the performance of PEP as a synchrotron radiation source. Possibilities being investigated include:

- further reduction of the emittance by means of damping wigglers or by changes in damping partition
- ways to produce very short bunches
- use of very long insertion devices
- use of insertion devices in chicanes and/or bypasses

A workshop on PEP as a Synchrotron Radiation Source, sponsored by the Stanford Synchrotron Radiation Laboratory (SSRL), was held at Stanford in October 1987. In the workshop proceedings,[2] many of these ideas are described in detail. Included in Ref. 2 is detailed information on the great scientific potential of PEP as a synchrotron radiation source, especially on those experiments made possible by the high brightness, peak power, coherent power, and extended spectral range of photon beams from the upgraded ring.

Recently, additional beam time was made available to allow a more complete characterization of the low-emittance lattice and its behavior in terms of collective effects. During the period from December 9-21, 1987, PEP was operated at 7.1 GeV in the low-emittance optics. The beam emittance was measured to be 5.3 ± 0.8 x 10^{-9} π m·rad, consistent with the calculated value of 6.4 x 10^{-9} π m·rad. Measurements made after increasing the damping partition number (by changing the RF frequency) gave an even lower emittance of 3.8 ± 0.5 x 10^{-9} π m·rad, in good agreement with the predicted value of 3.7 x 10^{-9} π m·rad. These results are described in other reports.[3,4]

In this paper, we describe the results of a study of collective effects for the low-emittance optics. In Section 2, we summarize briefly some of the information already known about PEP from previous studies with the collider optics, and show predicted behavior in the low-emittance optics based upon extrapolating the earlier results. Experimental results on single-bunch thresholds are discussed in Section 3, and Section 4 describes our observations of multibunch phenomena. Possible future experiments are outlined in Section 5; these will be useful in determining the ultimate performance of PEP for production of synchrotron radiation.

2. BACKGROUND

In this section we summarize some of the impedance information on PEP already known from previous experiments utilizing the collider optics. A more complete accounting of this information has been presented recently by Rivkin.[5] Over the past several years, PEP has been operated at a number of different energies, ranging from 4.5 to 14.5 GeV, and there is a considerable amount of data available on the impedance-related issues of bunch lengthening and transverse single-bunch instabilities.

The most recent bunch lengthening data,[6] measured at 4.5 GeV, are shown in Fig. 1. In Fig. 2(a) we show the fit—taken from Ref. 5—to the data in Ref. 6 with the code BBI.[7] Using a Q=1 broadband resonator centered at $f_r = 1$ GHz, a value of $|Z/n| = 2.5\ \Omega$ was obtained. An independent analysis[8] of the same results with the code ZAP,[9] and assuming an impedance roll-off with decreasing bunch length ("SPEAR scaling"), gave a value of $|Z/n| = 3\ \Omega$ (see Fig. 2(b)), in good agreement with the first result. We note that, although the appearance of numerous synchrotron sidebands in the bunch FFT spectrum was interpreted as the threshold for turbulent bunch lengthening in Ref. 6, this conclusion is *not* consistent with the analyses in Refs. 5 and 8.

Information on transverse impedance in PEP comes from observations of the transverse mode-coupling instability threshold. In Ref. 6, the single-bunch current limitation for the collider optics at 4.5 GeV was found to be 1.5 mA. As noted by Rivkin,[5] at the higher energy of 14.5 GeV the threshold increases to 8.4 mA. A calculation of the 4.5 GeV threshold with BBI, taken from Ref. 5, is presented in Fig. 3. In this calculation the expected transverse impedance was scaled from the longitudinal impedance in the usual manner, i.e.,

$$Z_\perp = \left(\frac{2R}{\beta b^2}\right)\left|\frac{Z_\parallel}{n}\right|$$

As can be seen in Fig. 3, the agreement with the experimental data is quite good. Thus, we conclude that the simple Q=1 broadband resonator impedance model is reasonably compatible with both longitudinal and transverse results at 4.5 GeV. A similar conclusion was reached from the analysis reported in Ref. 8.

Because the optics are different in the low-emittance mode than they are in the collider mode, some differences in transverse thresholds are anticipated. This is because the transverse threshold is not sensitive to the impedance itself, but rather to the impedance weighted by the local beta functions of the impedance-producing hardware. As indicated in Table 1, these beta values are significantly different in the region of the RF cells—which are known to dominate the ring impedance for the collider optics.

In the case of the low-emittance optics, we can use the above impedance model to make predictions of the beam behavior. In Figs. 4 and 5, respectively, we show the bunch lengthening and transverse mode-coupling behavior predicted[5] under the experimental conditions used in Ref. 1. As can be seen, significant bunch lengthening (about a factor of three) is expected. The transverse threshold is expected to manifest itself at a single-bunch beam current of about 2.5 mA.

Because of the availability of a large amount of RF power in PEP, it is also worthwhile to explore the benefits of utilizing it fully. (At present, it is believed that the many RF cells contribute about two-thirds of the observed ring impedance; we wish to consider whether the benefits of higher voltage outweigh the impedance "penalty" of having so many cells in the ring.) In Fig. 6, we show the predicted[5] behavior of the mode-coupling threshold as a function of applied RF voltage. At least on paper, there are clear benefits from utilizing higher voltage, and thus shorter bunches, to obtain roughly a fourfold increase in threshold current as the voltage is increased to its maximum value of 39 MV. Again, the calculations in Ref. 8 predict similar behavior.

Table 1

Beta Functions for Various PEP Optics[a)]

	IR		Region 2		<RF>		Undulator[b)]	
Optics	β_x*	β_y*	β_x	β_y	β_x	β_y	β_x	β_y
Collider	4.5	0.18	1.0	0.04	33.7	19.8	32.5	5.5
Low emittance	79	97	57	134	69.9	24.2	26.4	5.3
Modified low emittance[c)]	40	97	57	97	38.1	24.6	27.4	6.3

a) Beta functions in meters. IR refers to the center of the interaction region; Region 2 is the low-beta interaction region; <RF> corresponds to the weighted average value in the RF locations; Undulator corresponds to the center of the symmetry straight section.

b) Dispersion values at the undulator location for the various optics are: Collider, D_x = 1.49 m; Low emittance, D_x = 0.53 m; Modified low emittance, D_x = 0.30 m. Dispersion in other regions is zero.

c) Optics modified to reduce β_x in the IR and RF regions.

3. SINGLE-BUNCH THRESHOLDS AND STABILITY LIMITS

In this section we discuss our studies of single-bunch thresholds. In the work described here, we were unable to measure any effects due to turbulent bunch lengthening directly, so it was necessary to use predicted bunch lengths in our analysis. Based on the 4.5 GeV collider measurements described in Section 2, we expect a longitudinal impedance of $|Z/n| \approx 3\ \Omega$. This value was taken in subsequent estimates.

The momentum compaction factor for the low-emittance optics is a factor of 2.6 smaller than that for the collider optics, and leads to a threshold current for bunch lengthening at 7.1 GeV of roughly 0.6 mA. Thus, we are generally beyond threshold for the range of single-bunch currents studied here.

There are two transverse instabilities that might limit the single-bunch current in PEP: transverse fast blowup,[10] which is analogous to the well-known longitudinal microwave instability; and transverse mode-coupling,[11] which results from the coherent frequency shift of the beam due to the low-frequency inductive part of the transverse impedance.

In the cases of interest here, the bunch lengths are considerably shorter than the beam pipe radius. Thus, for the fast blowup threshold—which depends on the high-frequency portion of the impedance spectrum—we will assume that the effective transverse impedance seen by the beam is reduced from its low-frequency value due to the roll-off at frequencies beyond the beam pipe cutoff. That is, we apply the so-called SPEAR scaling approach[12] used to fit the PEP bunch lengthening results (see, e.g., Fig. 2). With this assumption, the threshold current is expected to arise from the transverse mode-coupling instability (see Fig. 5).

During the experiment, it was possible to monitor several aspects of the beam behavior. Total average current was monitored with a DC current transformer (DCCT) and a calibrated photodiode.

In practice, however, the response of the photodiode showed considerable sensitivity to the beam position, and thus was less useful in determining the beam current. Therefore, the threshold currents quoted here are taken from the DCCT readout.

An optical image of the beam, obtained from a synchrotron light monitor, was available on a TV screen in the control room. This was most useful in determining the behavior of the beam at the onset of instability. For example, the modulation of the beam shape gave clear indications whether the instability was arising from the horizontal or the vertical plane.

Pickup electrodes were available to view directly (via oscilloscope) or to drive an FFT analyzer. These electrodes could be combined either to give a peak current response or to give an enhanced sensitivity to horizontal or vertical motion. The FFT signal was monitored to obtain the betatron and synchrotron oscillation frequencies.

Threshold Determination

In our experiment, single-bunch thresholds were investigated by filling a single PEP RF bucket with beam from the SLAC linac until no further beam could be injected. The injection rate depended on the details of the linac tuning, and varied from a few tenths of a milliampere to a few milliamperes per minute at different times during the experiment. During the accumulation process, the beam generally was "quiet," in the sense that the optical image did not show significant changes in cross section and the FFT signal showed primarily the betatron tune lines, with few synchrotron sidebands.

When the beam current increased, the beam became noisier. The first indications came from the FFT, where the amplitude and number of synchrotron sidebands began increasing. As the injection process continued, beam blowup was observed with the synchrotron light monitor, and strong coherent oscillations were seen with the pickup electrodes. At this point, the injection rate fell to zero.

When accumulation stopped completely, the beam was very unstable. The FFT spectrum consisted of a picket fence of synchrotron sidebands. In addition, substantial effects were observed with the synchrotron light monitor: the beam centroid appeared to remain roughly fixed, but rapid and random changes of image size (by a factor of three) were seen. Finally, the pickup electrodes indicated significant coherent motion of the beam. As mentioned above, we define this point as the threshold current.

The typical pattern observed is shown in Fig. 7, which presents oscilloscope traces from the PEP beam pickup electrodes. Below threshold, the beam is quite stable (upper trace). When the threshold is exceeded (middle trace), the beam becomes quite unstable, and develops many synchrotron sidebands on the FFT spectrum analyzer used for betatron tune measurements (not shown). An increase in RF voltage from 9 to 11 MV (lower trace) was sufficient to once again stabilize the beam and permit further accumulation of current.

Our threshold results, which were remeasured at various times during the run, are displayed in Fig. 8 along with predictions based upon the transverse impedance found from the collider optics.[5] As is obvious, the observed threshold currents fall considerably below the predicted values. In terms of functional dependence, the data in Fig. 8 correspond roughly to $I_{thresh} \propto \nu_s^{0.8}$. In a simple estimate of the mode-coupling instability, the threshold depends linearly on the synchrotron tune.[9]

In our initial studies, it appeared from observation of the synchrotron light monitor that the instability shown in Fig. 7 was manifesting itself in the horizontal plane. This is in contrast to the "lore" for the PEP collider optics,[13] where the transverse mode-coupling instability has always been observed in the vertical plane. As can be seen in Table 1, the horizontal and vertical beta functions for the collider optics are quite different from the low-emittance optics studied here, most notably in the interaction regions (IR's). Clearly, this change could lead to an enhancement of the (beta-weighted) $Z_\perp$ values that determine the transverse threshold.

To get a measure of the transverse impedance seen by the beam, an experiment was done to measure the betatron tune shifts as a function of the single-bunch beam current, I_b; the data are shown in Fig. 9. From fits to the data we obtain slopes, $d\nu_\beta/dI_b$, of -0.0066/mA and -0.0075/mA for the horizontal and vertical planes, respectively.

To assess the corresponding transverse thresholds, we note that the tune shift corresponding to the mode-coupling instability in PEP occurs[14] at about three-quarters of the synchrotron tune separating the two modes ($m = 0$ and $m = -1$). (The calculations shown in Figs. 3 and 5 also yield this result.) Thus, we can estimate a threshold current for the instability by calculating the bunch current at which the tune shift has reached this value. Based on the data in Fig. 9, the corresponding threshold currents are 2.1 mA and 1.9 mA for the horizontal and vertical planes, respectively. The observed threshold of 1.5 mA is in rough agreement with these results. In the calculation, we predict the vertical threshold to be slightly lower than the horizontal—in contradiction with our observations—but the difference between the two slope values is not considered to be significant.

As mentioned (see Table 1), the horizontal beta functions in the RF regions and in the IR's are much larger than those from the collider optics. To test whether this was the reason for the lower than expected thresholds (see Fig. 8), we modified the low-emittance optics slightly to reduce the values of the horizontal beta function in both regions. The resultant β_x values are included in Table 1. Note that values of the vertical beta functions were virtually unchanged in the modified optics, so the gain, if any, would be expected to come from the horizontal plane.

After installing the modified optics configuration, we obtained an increase in the observed single-bunch threshold of about 50%, as shown in Fig. 8. Moreover, the character of the instability—as observed with the synchrotron light monitor—changed from the horizontal to the vertical plane.

To estimate the expected thresholds for the modified low-emittance configuration, we remeasured the betatron tune shifts as a function of current at two different RF voltages, 8.8 and 10.5 MV, with the results shown in Fig. 10. The values of the threshold current extracted from these data are summarized in Table 2. While not in quantitative agreement with the observed threshold current of 2.3 mA, the calculations clearly demonstrate that the reduction of the horizontal beta function makes the vertical threshold dominant, as was observed.

Still unexplained is the reason for the higher transverse impedance in the low-emittance optics compared with that scaled from earlier PEP collider data. It may be that the exceedingly high beta functions in the IR's are producing sensitivity to objects, such as synchrotron radiation masks, that contribute a negligible amount to the transverse impedance in the collider optics. Another possibility is that the significant orbit misalignments that were in evidence during the experiment are having a strong effect on our results. (Threshold variations of 50% have been seen previously[15] at PEP, even for the relatively well understood collider optics.) Further work will be required to understand this issue in detail.

Table 2

Tune Shifts and Mode-Coupling Thresholds

—Horizontal—

Optics	V_{RF} (MV)	ν_s	$\Delta\nu_x$/mA	I_{thresh} (mA)	Obs.
Low Emittance	6.3	0.0186	-0.0066	2.1	1.5
Modified Low Emittance[a)]	8.8	0.0221	-0.0034	4.9	>2.1
Modified Low Emittance[a)]	10.5	0.0242	-0.0045	4.0	2.3

—Vertical—

Optics	V_{RF} (MV)	ν_s	$\Delta\nu_y$/mA	I_{thresh} (mA)	Obs.
Low Emittance	6.3	0.0186	-0.0075	1.9	1.5
Modified Low Emittance[a)]	8.8	0.0221	-0.0096	1.7	>2.1
Modified Low Emittance[a)]	10.5	0.0242	-0.0094	1.9	2.3

a) Modified to reduce the β_x values in the IR's and RF regions. See Table 1.

4. MULTIBUNCH PHENOMENA

When PEP is used as a collider for high energy physics experiments at 14.5 GeV, it is run with only 6 bunches (3 electron and 3 positron); the total electron current is only 15-20 mA. However, for PEP to serve as a dedicated synchrotron radiation source, it is desirable to operate at lower energies and to achieve a circulating current on the order of 50-100 mA. In a ring such as PEP, which utilizes a high-frequency (353-MHz) RF system,[16] such intensities may not be practical unless many RF buckets are filled. Thus, we must explore the behavior of the PEP ring when operated in a multibunch mode.

The multibunch operating scenario was investigated in Ref. 8, where it was concluded that the growth times for longitudinal coupled-bunch instabilities would be on the order of 1 ms for currents above a few milliamps. Transverse coupled-bunch instability growth times were predicted to be somewhat longer, about 5-10 ms. Since the damping time at an energy of 7 GeV is about 40 ms, there was reason to be wary.

Coupled-bunch instabilities are driven by the higher-order modes of the PEP RF system,[16,17] which comprises 24 five-cell RF stations capable of providing up to 39 MV. The PEP RF cells are not mechanically identical, the cavity apertures for different RF stations being tailored to follow the beam optical functions. This means that the higher-order modes of the various RF cells will not simply add up. In practice, the resonant frequencies and bandwidths (or Q's) of the higher-order cavity modes also depend significantly on the operating conditions—beam loading, cavity voltage, temperature, auxiliary tuner position, coupling to the RF amplifier—of each accelerating station.

Although the identity of the RF mode driving a particular instability can vary, and thus the corresponding threshold current for the instability can change, as a rule it is unlikely that overall performance can be radically changed by adjustments to the RF system operation. A possible exception to the previous statement concerns the fundamental (accelerating) mode, since the cavities are designed and tuned to have identical center frequencies, high impedance, and high Q for this mode. We will return to this point later.

To mock up the effects of the many similar—but not identical—RF cells, we have combined the modes listed in Ref. 17 by "de-Qing" them; that is we reduce both the Q and the shunt impedance of the individual higher-order modes. This approach effectively broadens the resonances to correspond to the displacement of resonant frequencies of the various modes in the different RF cells. The prescription we employ here is to take the modes for a single RF cell, *increase* the shunt impedances by a factor of 6, and *reduce* the Q values by a factor of 20. (This approach keeps the overall strengths of the modes, characterized by R_S/Q, to values compatible with the total set of 120 cells.) Our choice of parameters is certainly not unique, but should give an order-of-magnitude estimate of the coupled-bunch instability growth rates. (A few calculations were performed using a different de-Qing procedure—taking $24R_S$ and Q/5. Compared with our adopted prescription, the resultant growth times decreased by about a factor of three. The extreme of not de-Qing at all would decrease the calculated growth times by about a factor of ten.) Resultant higher-order mode parameters (ω_r, R_S, Q) used in the calculations reported here are collected in Table 3.

In the experiments discussed below, several different issues were investigated. First, we explore the topic of bunch-to-bunch interactions phenomenologically. The goal here was to see whether we could empirically define a suitable procedure for filling the ring in the multibunch mode. Next, we looked at the benefits of using one of the "idle" PEP RF stations as a tune-splitting cavity to reduce the coupled-bunch interactions via Landau damping. Finally, we considered the effects of the many idle RF stations on the beam stability.

Phenomenology

In the initial experiments, we were trying to ascertain the limitation on beam current that could be stored in the multibunch mode and to explore various filling patterns to see how they affected beam stability.

One topic of interest was to determine the distance over which the wake field of one bunch could strongly influence the motion of a following bunch. Since PEP has a circumference of 2.2 km and a 353-MHz RF system, the distance between successive bunches can be varied from 85 cm to 1.1 km. In the experiment, one bunch was filled to about 1.5 mA (i.e., essentially to the single-bunch current limit) and a second bunch was then filled to its current limit. The trailing bunch was initially located 863 RF buckets behind the first (one-third of the circumference) and then, after dumping the ring and restoring the first bunch, the distance of the trailing bunch was successively halved.

Had the first bunch been seriously affecting the second, we might expect that the current attainable in the second bunch would depend on the relative spacing between bunches. These measurements, however, showed no clear trend of maximum current with bunch separation. Indeed, typical variations were only about 3% over the entire range of bunch spacing, which is not considered significant.

Next, we briefly tried to use two adjacent bunches followed by a third bunch as a probe. In this case we observed that the maximum current attainable in the third bunch increased with decreasing distance from the pair of leading bunches.

Since it appeared that close spacing of bunches was not incompatible with their survival, we subsequently explored filling patterns consisting of several strings of adjacent bunches separated by gaps of empty RF buckets. Several variations on this theme were tried, with no clear advantage to any of them. For example, leaving large gaps between bunch strings gave no benefit compared with smaller gaps, and distributing the strings uniformly around the circumference gave results equivalent to a nonuniform pattern. In all cases, a total beam current of about 12-15 mA was achieved. Beyond this current, the beam became violently unstable and many bunches were lost from the ring.

A successful scheme for reaching reasonably high currents in a reproducible fashion was to run with many closely spaced bunches (e.g., tens of RF buckets apart), each with a low current (about 0.1-0.25 mA per bunch). In this way, 10-20 mA could be stored with lifetimes in excess of one hour. (Even higher currents were sometimes reached, but not reproducibly.) It was observed in this mode that the presence of a single large bunch in such a string (caused, for example, by an accidental overfilling) was enough to produce beam loss.

Tune Splitting

One technique for controlling longitudinal instabilities that was investigated during the PEP studies was the use of a tune-splitting RF cavity.[18] To produce a different synchrotron tune for different bunches, one of the 24 accelerating stations was tuned and driven at the h = 2593 rotation harmonic, one rotation harmonic above the normal accelerating frequency. When phase-locked to the accelerating RF, adjacent bunches see a different voltage, and thus have a different synchrotron tune. As illustrated in Fig. 11, the resultant tune modulation is roughly proportional to the sine of the azimuth around the ring. For the parameters employed in this study (V_{RF} = 6.5 MV, $V_{splitter}$ = 1-2 MV), it was possible to modulate the tune in the range of $f_s \approx 2.3 - 2.8$ kHz as a function of the azimuthal position in the ring.

After powering the tune splitter, and ascertaining the proper phase with two diametrically opposite bunches, the ring was loaded so as to maximize the tune difference between adjacent bunches. Ultimately, we were able to store about 20 mA in this manner. Insofar as the chosen tune-splitter parameters were not limited by the hardware, it may well be that additional voltage would have increased the threshold further. Unfortunately, there was some question about the stability of the tune-splitter hardware, so definitive results on the efficacy of this approach must await additional measurements.

Effects of Idle RF Stations

The 353.21 MHz PEP cavities have a loaded bandwidth of 44 kHz, whereas the rotation frequency is 136.27 kHz. Thus, as pointed out by Pellegrini and Sands,[19] the accelerating resonance *itself* can drive longitudinal instabilities. For PEP colliding-beam running, the difficulty was remedied with a feedback system.[20] ZAP computations performed during and after the experiment have shed some light on the observed phenomena. Results for the various scenarios considered are summarized in Table 4.

In the typical running mode used for the 7.1 GeV studies reported here, only six RF stations were powered to provide about 6 MV peak voltage. The other eighteen RF stations were unpowered and "parked," i.e., their tuners were located so as to give a resonant frequency approximately midway between the h = 2591 and h = 2592 (accelerating) rotation harmonics. In this circumstance, the idle acceleration mode of all the unused cells lines up essentially perfectly.

For a small number of equally spaced bunches, ZAP predicts that the "k_b-1" sideband (where k_b is the number of stored bunches) will be driven by the idle cavities, with a typical growth time of a few milliseconds. By monitoring this sideband at the onset of beam loss, measured growth times of 2.5 ms (with 16 mA in about 60 bunches) and 4.3 ms (with 6 mA in about 20 bunches) were obtained, in reasonable agreement with the predictions.

The computed growth time increases (see Table 4) if one of the 18 unpowered stations is tuned to the h = 2593 harmonic (to serve as a tune splitter, as described above). Thus, even with zero applied voltage in the tune-splitter cavity, the beam would be expected to be more stable if only a few bunches are stored.

An attempt was made to cancel the contribution of the idle cavities to the coupled-bunch driving impedance by parking them symmetrically around the acceleration frequency, that is, tuning nine stations 68 kHz (half a rotation harmonic) *above* the 353.21-MHz accelerating frequency while leaving the other nine stations an equal amount below this frequency. For three equally spaced bunches, ZAP predicts slower growth of the instability for this RF cavity arrangement.

Experimentally, when the tune-splitter cavity was employed in this configuration, the beam stability was slightly worse, and no more than 16 mA could be stored. Because the impedance of the tune-splitter cavity itself contributes to destabilizing the k_b-1 mode, it was finally turned off and parked at its normal idle location. Beam stability improved thereafter. The best observed performance, with the idle RF stations parked symmetrically, but without the use of the tune-splitting system, was 33 mA. Although not investigated during the experiment, our calculations indicate that similar benefits would be expected if the idle cavities were all tuned to resonance with the accelerating harmonic.

It is clear that optimum parking of the idle RF stations can completely cancel the destabilizing effects of their fundamental resonances. Unfortunately, our calculations show (see Table 4) that the destabilizing influence of the higher-order parasitic modes should dominate that of the accelerating modes, causing instability for beam currents at or below those observed to be stable during the experiment. Only in the worst-case tuning arrangement, with all of the idle stations parked low, do we predict the fundamental mode to give contributions to the instability comparable to those from the parasitic modes. Nevertheless, there did appear to be some benefit (in terms of stored beam current) to the symmetric parking arrangement compared with the normal configuration. This observation may be related to changes in location of the parasitic modes of the idle stations when the tuner positions were adjusted.

Table 3

PEP RF Cavity Modes Used in ZAP Calculations[a)]

ω_r (MHz)	R_s (MΩ)	Q_{eff}
2219.145	66.0	8000
2218.856[b)]	198.0	8000
2219.712[c)]	99.0	8000
2220.142[d)]	11.0	8000
3186.8	12.2	1825
5550.6	3.2	2725
5818.9	8.9	1790
7333.1	3.7	2530
9048.4	2.6	4575
9094.3	3.3	3035
12794.8	4.8	3575

a) Frequencies taken from Ref. 17. Q values for all modes except the fundamental were reduced by a factor of 20; shunt impedances were increased by a factor of 6.

b) Location of idle cavities (18 out of 24 stations). This is referred to as "parked low" in Table 4.

c) Location of idle cavities (9 out of 24 stations). This is referred to as "parked high" in Table 4. The shunt impedance of the other parked stations was reduced accordingly when these stations were used.

d) Location of tune-splitter station. The shunt impedance of the other parked stations was reduced accordingly when this station was used.

Table 4

PEP Coupled-bunch Growth Time Predictions[a)]

Case	k_b=	3	6	9	18	36	72
parked low		18.6	16.6	5.0	3.5	2.1	0.9
parked symmetrically		46.4	19.2	4.8	3.3	2.1	0.9
parked on resonance		36.3	19.7	4.8	3.3	2.1	0.9
parked on resonance; no de-Q		1.3	0.7	0.6	0.3	0.1	0.1
tune splitter; parked low		31.9	20.6	4.9	3.4	2.1	0.9
tune splitter; parked 9 low, 8 high		367.6	18.9	4.7	3.3	2.0	0.9
tune splitter; parked on resonance		150.9	19.3	4.8	3.3	2.1	0.9

a) ZAP predictions; all growth times in milliseconds. Modes from Table 3 were used as appropriate for the case in question. A beam current of 0.5 mA per bunch was assumed in all cases.

5. FUTURE WORK

Single-bunch Mode

In the present study, we have found that the transverse mode-coupling instability limits the single-bunch current to only a few milliamperes. It is likely—though not proven—that the main impedance contribution in the low-emittance lattice is still coming from the RF system. It is important to understand whether or not there *are* unexplained differences between the low-emittance and collider optics. There are several approaches that could be followed:

- *Provide better control of the orbit in the RF regions.* It would be informative to examine the sensitivity of the single-bunch threshold and/or the betatron tune shift with current to the alignment (or misalignment) of the beam orbit in this area. Additional correction elements would probably be needed.
- *Measure the bunch length with a streak camera* to verify the longitudinal parameters used in the mode-coupling calculations.
- *Short out or remove some of the existing RF stations* to see how the thresholds behave. Ideally, this would be accomplished in a reversible manner, so that unambiguous comparisons could be made and so that compatibility with collider running would be maintained. Plans for this experiment should be guided by calculations of the effects on both single-bunch and multibunch behavior.
- *Find alternative lattice optics* that permit the disentangling of the impedance contributions from the RF regions and the interaction regions by suitable changes to the beta functions. This was attempted during the experiments discussed here, but did not give unambiguous results.

Multibunch Mode

In this case, the experiments confirmed the earlier predictions[8] that coupled-bunch instabilities would be a serious concern. Although some progress has been made in storing up to 33 mA, the results obtained were not very reproducible. Future efforts should be aimed at a quantitative understanding of the resonant ring impedances, and at achieving reproducibility of results. To this end, we note that the availability of automatic control of multibunch filling patterns will be an essential ingredient of any future systematic studies. It will also be important to confirm the assumptions on parasitic modes that were used in the ZAP calculations; no beam time would be required for this purpose.

There are several options available that should give the possibility of storing the required 50-100 mA beam current stably and reproducibly:

- *Continue efforts with the tune-splitter technique.* If a stable system is available, and can be operated at reasonably high voltage, it should help damp the growth of the longitudinal instabilities.
- *Add damping loops for the most damaging higher-order modes.* Provision for this exists in the present RF cell design, although it has never been implemented. Calculations may give useful guidance here, provided that the observed growth rates can be associated with a few particular modes—but this is not necessarily the case.
- *Remove or short out some of the presently installed RF stations.* An increase in growth times of about a factor of three might be gained this way. This might already be sufficient to give a 50-100 mA beam current.
- *Install a Landau cavity* in the ring. Such a system, involving a higher harmonic of the 353-MHz RF, will produce longer bunches having a larger synchrotron tune

spread—features that will greatly reduce the coupled-bunch instabilities in PEP. With proper phasing, such a system also provides the possibility of shorter bunches, which would be beneficial for certain types of fast-timing experiments.

- *Provide a longitudinal feedback system* to combat the instabilities. Should this be needed, its requirements would be lessened if it were used in conjunction with some of the other "cures" listed above. It would be prudent, then, to postpone consideration of this possibility until some assessment of the efficacy of the (more or less) passive techniques takes place.

6. SUMMARY

In this paper we have presented the results of experiments aimed at evaluating collective effects for the PEP low-emittance optics configuration. The measurements were carried out at a beam energy of 7.1 GeV, during the period from December 9-21, 1987.

Single-bunch thresholds have been determined as a function of RF voltage. The observed single-bunch current limits are about half those predicted using the presently accepted impedance information derived from experiments using the PEP collider optics. Reducing the horizontal beta functions at the RF stations and in the interaction regions increased the threshold by about 50%, and appeared to change the instability from the horizontal to the vertical plane. It is not clear at present why the observed thresholds are lower than expected. It may be that the larger beta functions in the straight sections are giving rise to significant beta-weighted transverse impedance due to objects that are unimportant with the normal low-beta collider optics. Alternatively, the lower threshold may result simply from the relatively poor control of the orbit in the RF regions. More experimental work will be needed to clarify this.

Multibunch running was also investigated. This work was in the nature of a reconnaissance to quickly establish whether interesting beam intensities were available, with suitable stability, from the PEP low-emittance lattice. This goal was successfully achieved. A reasonably stable beam of 15 mA was obtained by filling the ring with many low intensity bunches. Use of one RF station as a tune-splitter cavity was explored, with mixed success. There may have been hardware problems that limited the effectiveness of the technique, however, so further work will be required on this topic. By adjusting the tuner positions of the idle RF stations, up to 33 mA of beam was stored. The beam was somewhat unstable in this case, however, and was probably unsuitable for synchrotron radiation experiments. Calculations of the expected coupled-bunch growth rates are in reasonable agreement with those observed. In future work, it will be worthwhile to explore alternative cures for this problem. Possibilities include: removal (or shorting out) of the unused RF stations; damping of the higher-order RF modes; addition of a Landau cavity; or active multibunch feedback.

No fundamental problems have been discovered that would preclude the effective use of PEP as a dedicated synchrotron radiation source.

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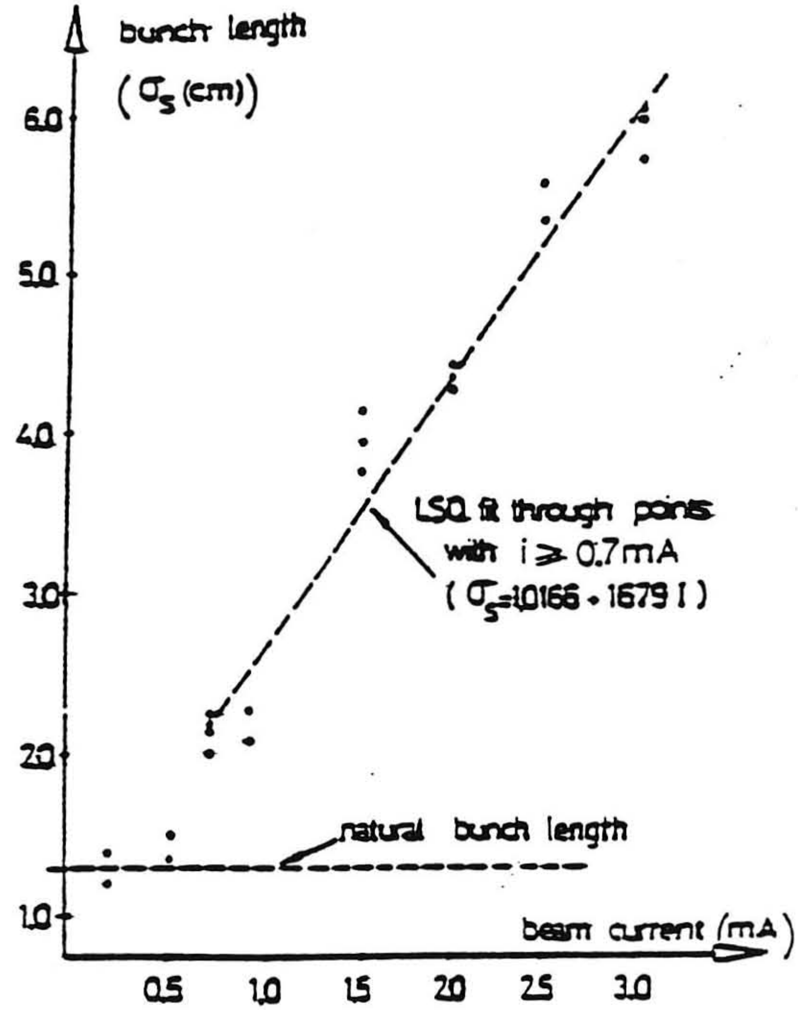
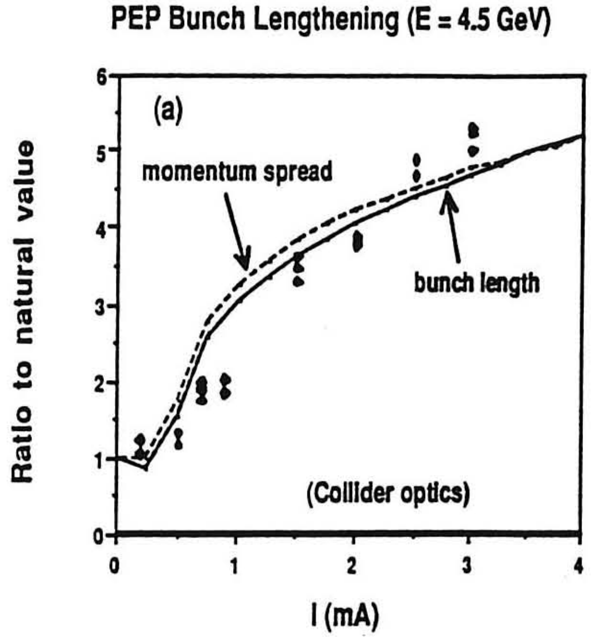


Fig. 1 Results of PEP bunch lengthening measurements, using collider optics, at 4.5 GeV. Taken from Ref. 6.



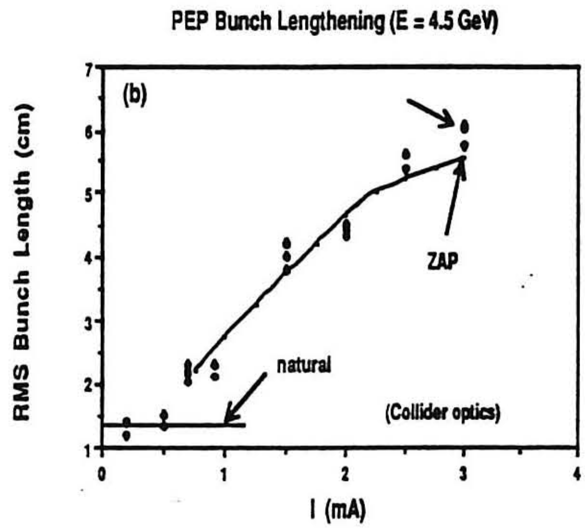


Fig. 2 (Top) Bunch lengthening predictions from BBI, plotted as the ratio of $\sigma_\ell/\sigma_{\ell o}$ (bunch length) and $\delta p/\delta p_o$ (momentum spread), where $\delta p = \sigma_p/p$. The points are experimental results from Ref. 6 (see Fig. 1).

(Bottom) Absolute bunch lengthening results from ZAP. Data points are from Ref. 6.

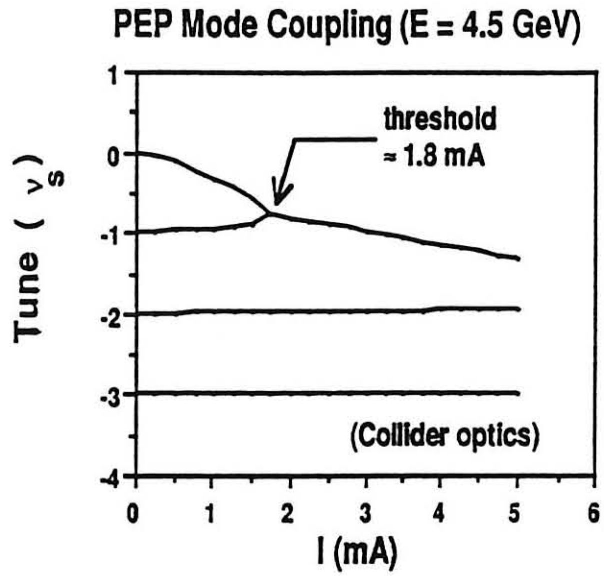


Fig. 3 Mode-coupling calculations for PEP collider optics. The Q=1 broadband resonator was centered at 1 GHz, and had a transverse impedance of 0.6 MΩ/m. Calculations from Ref. 5.

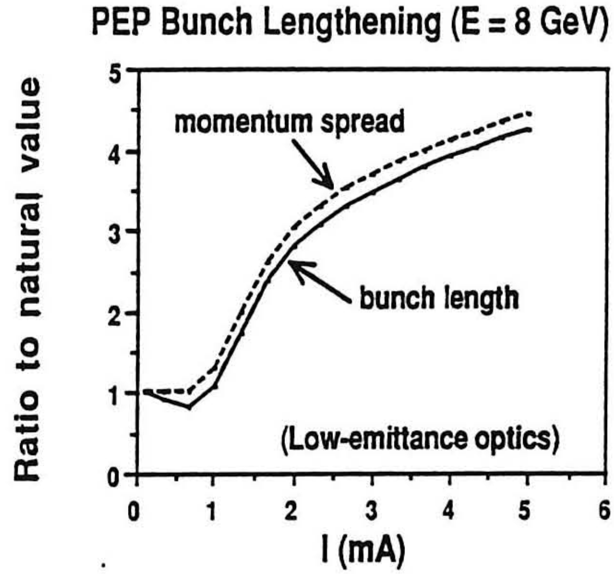


Fig. 4 Bunch lengthening predictions from BBI, for the PEP low-emittance optics at 8 GeV. Results are plotted as the ratio of $\sigma_\ell/\sigma_{\ell o}$ (bunch length) and $\delta p/\delta p_o$ (momentum spread), where $\delta p = \sigma_p/p$.

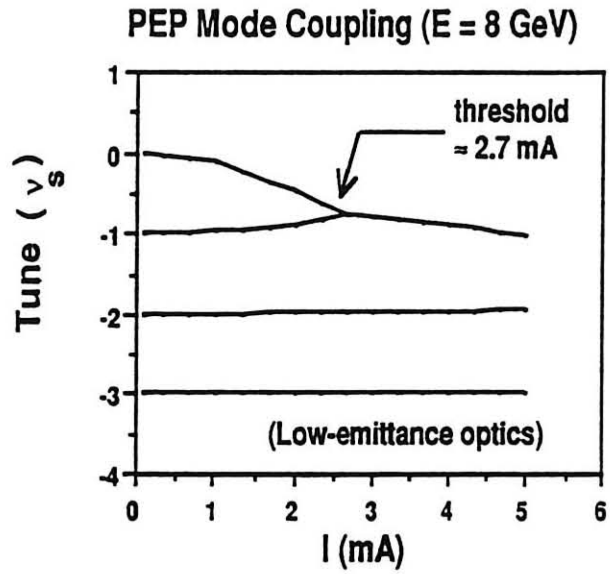


Fig. 5 Mode-coupling predictions for the PEP low-emittance optics at 8 GeV.

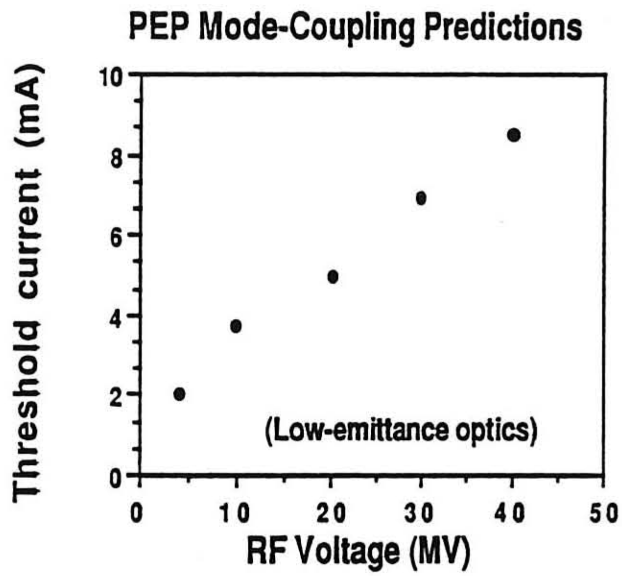


Fig. 6 Predicted mode-coupling threshold current as a function of applied RF voltage. Calculations from Ref. 5.

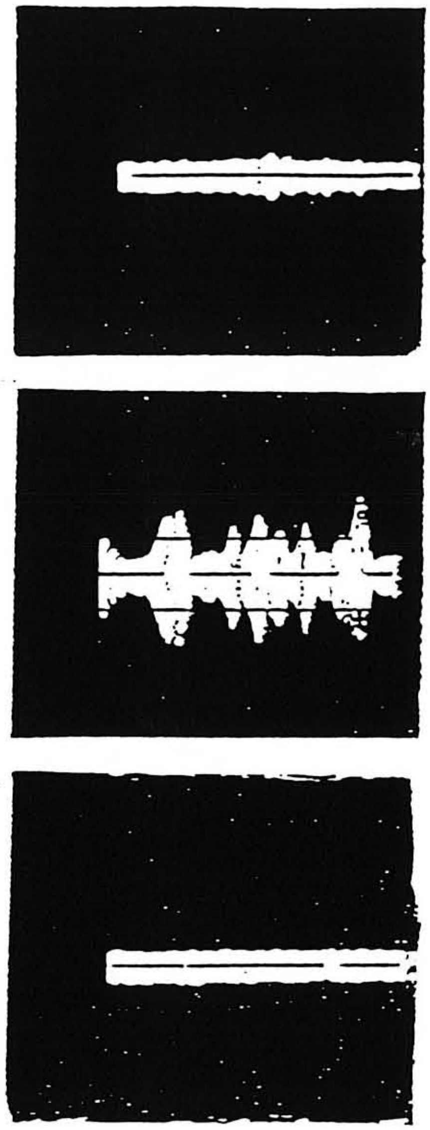


Fig. 7 **Oscilloscope traces** from a PEP beam pickup electrode **triggered on the injection pulse.**

Top: **1.51 mA;** V_{RF} = 8.95 MV.

Center: **1.62 mA;** V_{RF} = 8.95 MV.

Bottom: **1.60 mA;** V_{RF} = 11.0 MV.

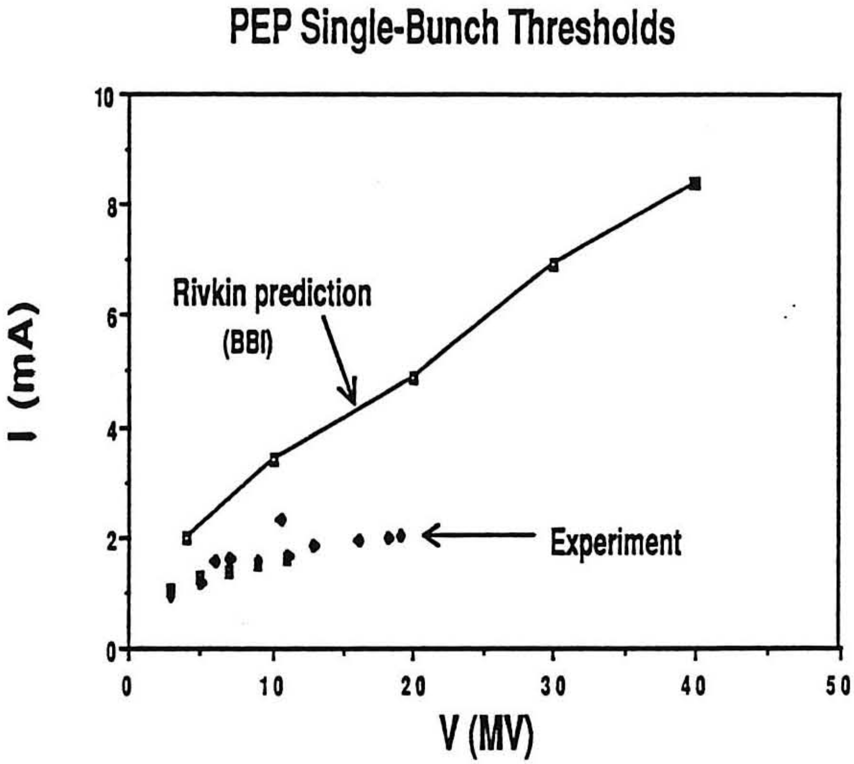


Fig. 8 Predicted and observed single-bunch thresholds for the PEP low-emittance optics at 7.1 GeV. Predicted values are taken from Ref. 5.

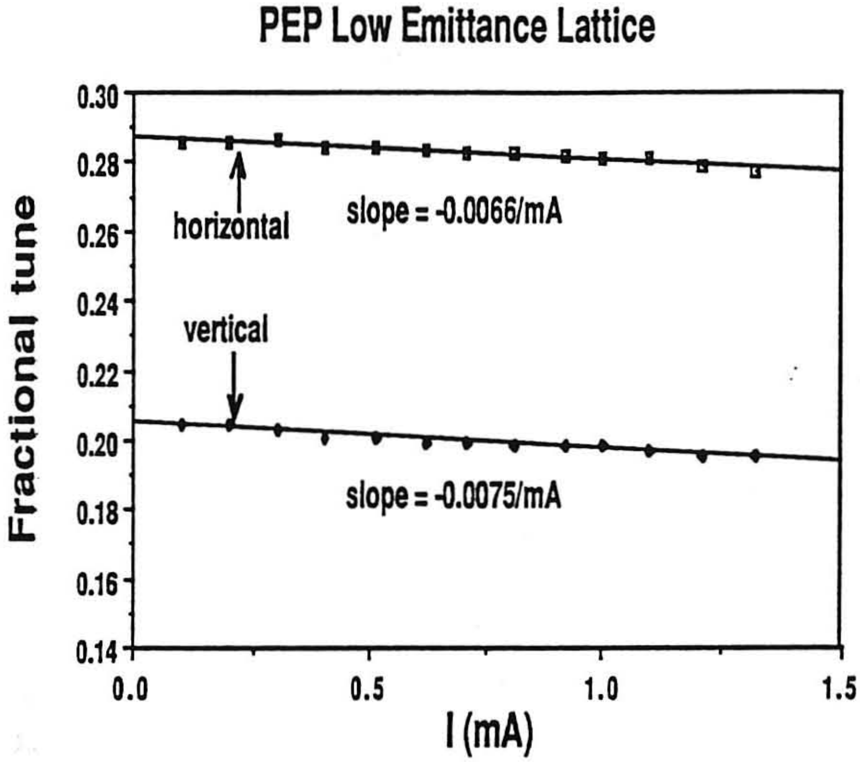
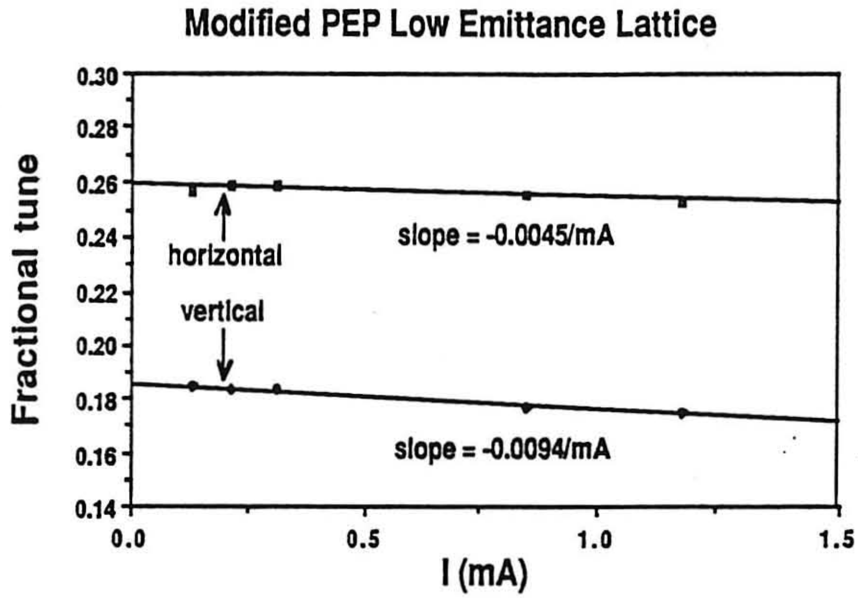


Fig. 9 Change in betatron tune with current for PEP low-emittance optics. The slope values correspond to a predicted threshold of about 2 mA, compared with 1.5 mA found experimentally.



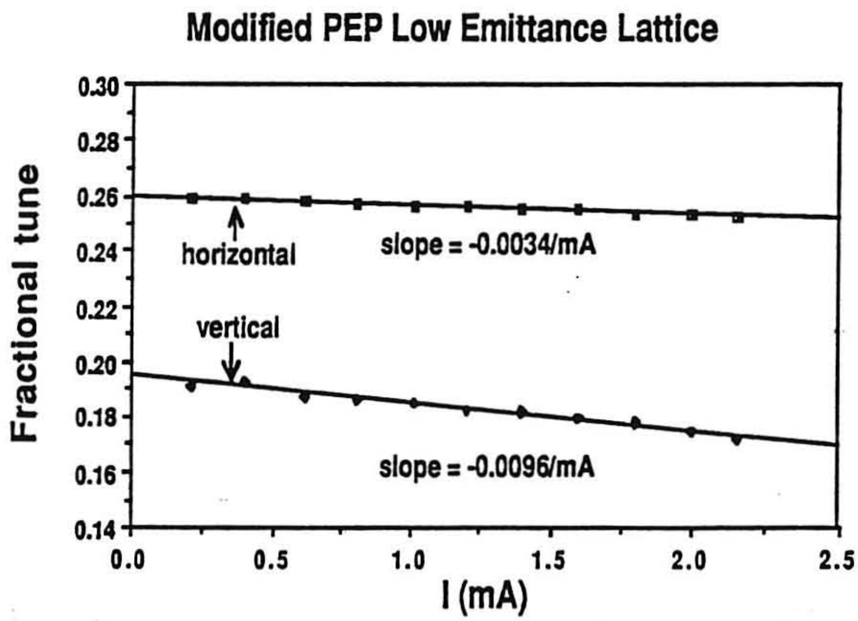


Fig. 10 As in Fig. 9, but for the modified low-emittance optics. The reduced slope for the horizontal tune corresponds to a higher threshold in this plane. The vertical behavior is essentially unaffected. The upper graph is measured at $V_{RF} = 10.5$ MV, the lower graph at $V_{RF} = 8.8$ MV.

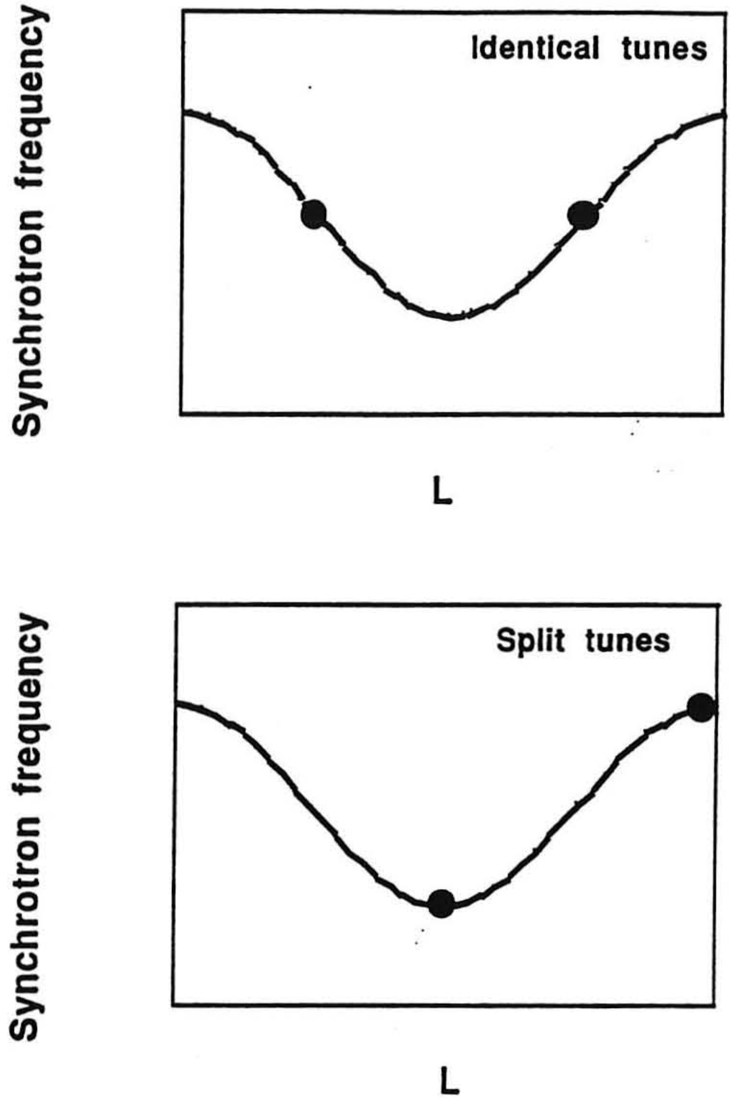


Fig. 11 Schematic representation of the synchrotron frequency modulation, at ring position L, resulting from the tune-splitting cavity. By changing the phase of the tune splitter, two diametrically opposite bunches can be made to have identical (upper) or split (lower) tunes. In the experiment, bunches were located in the region near one of the two drawn in the upper graph. This gives maximum tune splitting for adjacent bunches.