SLAC-PUB-8202
February 2000

Recent Beam-Beam Experience with Multiple High Current Bunches in PEP-II

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Invited talk presented at Workshop on Beam-Beam Effects in Large Hadron Colliders, 4/12/99—4/16/99, Geneva, Switzerland

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Work supported by Department of Energy contract DE–AC03–76SF00515.

RECENT BEAM-BEAM EXPERIENCE WITH MULTIPLE HIGH CURRENT BUNCHES IN PEP-II *

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Abstract

Operation with colliding beams at PEP-II has progressed remarkably well with over half the design specific luminosity and 5.2×10^{32} cm^{-2}s^{-1} in multiple bunches demonstrated during the last commissioning period before installation of the BABAR detector. Further luminosity increases are anticipated as the vertical beam size is reduced and beam currents are raised towards design values. At high currents interesting multibunch dynamics, which depend strongly on current distribution, have been observed during single-beam commissioning studies. Transverse beam instabilities nominally controlled using bunch-by-bunch feedback were observed to be significantly suppressed, in the absence of feedback, with beams in collision.

1 OVERVIEW

A PEP-II overview showing the injector subsystems, the positron low-energy ring (LER, top) and the electron high-energy ring (HER, bottom) is shown in Fig. 1. The SLAC linac is a powerful and time-efficient injector for PEP-II. In the linac, both electron and positron beams are accelerated to smaller than required beam emittances and to the required beam energies of 9.0 and 3.1 GeV respectively. Since the relative rf phase of the PEP-II rings is maintained constant, different bunches are filled by shifting the beam timing in upstream accelerator subsystems. With up to 850 μA per pulse in the linac, it is anticipated that less than 3 minutes will be required to fill PEP-II to the design beam currents of 0.75 A electrons and 2.1 A positrons at a reduced repetition frequency of 60 Hz. The design bunch population consists of 1658 equidistant bunches with a 5% ion clearing gap.

A comparison of some selected PEP-II design parameters with those achieved to date prior to installation of the BABAR detector is given in Table 1. The specific luminosity has already been measured to be over one-half of design [1]. The luminosity measurements are made with a radiative Bhabha detector. A recent cross-calibration with a crystal-ring detector, displaced 17 cm from the IP detecting electrons and positrons at 90 degrees in the center of mass, showed excellent agreement.

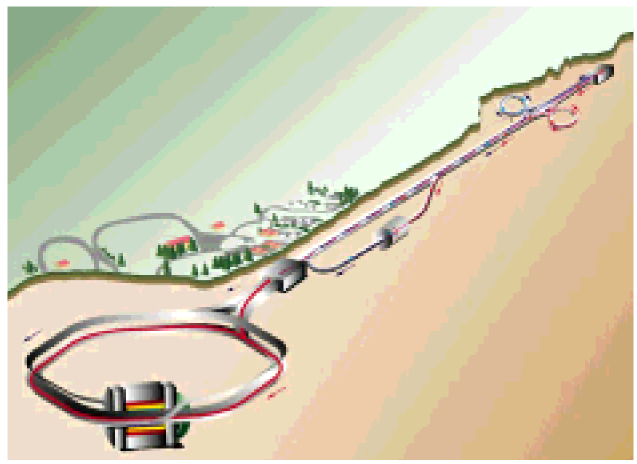

Figure 1: Overview of SLAC linear accelerator showing injection into the PEP-II asymmetric collider including the BABAR detector which is presently being installed.

During colliding beam experiments, the PEP-II beams have mostly been injected while maintaining head-on collisions. Occasionally the beams were separated at the interaction point (IP) with a relative vertical IP orbit offset of about 100 μm. Longitudinally once the beam arrival times at the IP have been measured and set (at the start of a collision shift), the rf phase is held constant. The optical functions also remain fixed between injection and establishing collisions. High luminosity experiments to date indicate that the 150 ms interval used for reducing the last $3\Sigma_y$ of vertical separation is sufficient not to cause significant beam loss. The speed of the final alignment of the beams may require further study at higher beam currents with emphasis on the beam-beam induced backgrounds which will be measured by the BABAR detector.

* Work supported by the Department of Energy, contract DE-AC03-76SF00515 for SLAC, DE-AC03-76SF00098 for LBNL, and W-7405-Eng-48 for LLNL

Parameter	design	achieved
E_{e^-} (GeV)	9.0	9.0
E_{e^+} (GeV)	3.1	3.1
$I^{tot}{}_{e^-}$ (A)	0.75	0.75
$I^{tot}{}_{e^+}$ (A)	2.14	1.17
$N^{ppb}{}_{e^-}$	2.1×10^{10}	4.2×10^{11}
$N^{ppb}{}_{e^+}$	5.8×10^{10}	3.2×10^{11}
N_c (total)	1658	1571
$\beta^*{}_{x,e^-}$,$\beta^*{}_{y,e^-}$ (cm)	50, 1.5	50, 1.5
$\beta^*{}_{x,e^+}$,$\beta^*{}_{y,e^+}$ (cm)	50, 1.5	50, 1.5
σ_{z,e^-},σ_{z,e^+} (cm)	1.1, 1.2	1.2, –
Σ_x,Σ_y (μm)	220, 6.6	220, 12
ν_{x,e^-},ν_{y,e^-}	24.57, 23.64	24.57, 23.59
ν_{x,e^+},ν_{y,e^+}	38.57, 36.64	38.61, 36.58
ν_{s,e^-}	0.045	0.045
ν_{s,e^+}	0.033	0.026
ξ_{x,e^-},ξ_{y,e^-}	0.03, 0.03	0.020, 0.009
ξ_{x,e^+},ξ_{y,e^+}	0.03, 0.03	0.030, 0.015
L ($cm^{-2}s^{-1}$)	3×10^{33}	5.2×10^{32}
L_{sp} ($cm^{-2}s^{-1}mA^{-2}$)	3.11×10^{30}	1.71×10^{30}

Table 1: PEP-II design parameters and those achieved as of February 1999 including the beam energies E_{e^-} and E_{e^+}, total current I^{tot}, the charge per bunch N^{ppb}, the total number of bunches used in collision N_c, the IP beta functions β^*, the bunch lengths σ_z, the effective IP spot size $\Sigma_{x/y} = \sqrt{\sigma^2{}_{x/y,e^-} + \sigma^2{}_{x/y,e^+}}$, where σ is the single-beam IP spot size, the betatron and synchrotron tunes ν_x, ν_y, ν_s, the incoherent beam-beam parameters ξ_x and ξ_y, the total luminosity L, and the specific luminosity L_{sp}. The listed beam currents indicate obtained peak values. Below the line the parameters correspond to the peak measured luminosity for which $I^{tot}{}_{e^+} = 680$ mA (limited at the time of this measurement to below 700 mA by chamber heating) and $I^{tot}{}_{e^-} = 354$ mA in $N_c = 786$ colliding bunches.

With a head-on collision geometry at the single IP, parasitic crossings are of some concern. The beam trajectories are magnetically separated using strong dipoles located ± 21 cm from the IP. With the bunches spaced by only 4.2 ns in the design fill pattern, there are 4 parasitic crossings spaced longitudinally by 0.63 m on either side of the IP. It is expected [2] that only the first of these, where the beams are transversely separated by about 3.5 mm, is non-negligible. Long range beam-beam interactions with the design fill pattern have not yet been extensively explored as collider commissioning has necessarily taken place at reduced total beam current thus allowing for increased bunch spacings. A brief experiment at the nominal bunch spacing with 1571 bunches, a 10% gap, and I_{e^+}:I_{e^-} currents of 680:440 mA showed no appreciable change in specific luminosity but a slight degradation in capture efficiency at injection.

In this report we first summarize the knowledge gained with beams in collision at PEP-II to date (section 2). We then focus on multibunch beam dynamics as observed first during single-beam commissioning studies (section 3) and later with high current, multibunch beams in collision (section 4). In particular we demonstrate with experimental data that the nonlinearity of the beam-beam interaction significantly stabilizes collective beam instabilities. A conclusion and outlook is presented in section 5.

2 RECENT COMMISSIONING RESULTS

Since the completion of the LER in the summer of 1998, about 20 days have been dedicated to colliding-beam experiments [3]. The sequence used for establishing colliding beams includes the following. First the beams are longitudinally phased roughly to within about $0.3\,\sigma_z$ using the beam arrival time at two shared beam position monitors (BPMs) located at 0.72 m on either side of the IP. Next the trajectory of the positron beam through the IP is adjusted for optimal centering on the radiative Bhabha luminosity monitor. The electron beam is then steered, using the same BPMs to determine the relative position offsets, for head-on collisions. The position resolution of the monitors is effectively about 5 μm. Each ring is then decoupled for a minimum tune separation of $< 10^{-3}$ and the residual vertical dispersion η is nominally corrected to be less than 1 cm rms in the accelerator arc regions. The residual dispersion at the IP, which is measured by taking the sum (η) and difference (η') of the two IP BPMs at different accelerating frequencies, was typically corrected to be less than 1 mm.

2.1 Betatron Tunes

During early commissioning with single beams, experiments were undertaken to find optimal operating points in the tune diagram for each ring [4]. These studies revealed a preference, in terms of long beam lifetimes, for betatron tunes in the LER below the major diagonal. In the HER, based on maximum luminosity, the fractional horizontal and vertical betatron tunes were set nearly equal (but with a difference in fractional tunes still more than the minimum tune separation) and with the vertical betatron tune almost equal to the vertical positron tune. With beams in collision, the tune window was observed to be less than $(2{-}3)\times10^{-3}$ at the highest beam luminosity. As the beam currents were increased while maintaining collisions, it was also found necessary to correct the electron beam orbit and to continually maintain its betatron tunes which changed due to the current dependence of short-range wakefields.

2.2 Collisions at Low Beam Currents

The measured luminosity at low beam currents improved with each collision run as the beam trajectories and optics continued to converge towards design values. Shown in Fig. 2 is the luminosity measured using the radiative Bhabha monitor during horizontal (top) and vertical (bottom) beam-beam scans at low beam current after successive iterations of local coupling and dispersion correction.

As will be discussed further, in contrast to data taken with strongly interacting beams, these measurements are well represented by Gaussian distributions. The beam size overlap, from the Gaussian fits was $\Sigma_x = 215 \pm 6$ μm horizontally and $\Sigma_y = 8.6 \pm 0.2$ μm vertically.

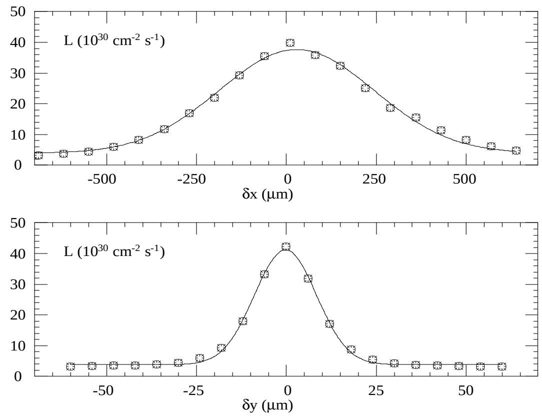

Figure 2: Measured luminosity as a function of horizontal (top) and vertical (bottom) beam separation at the IP with $\mathrm{N_c} = 786$, $\mathrm{I^{tot}}_{e^+} = 280$ mA, and $\mathrm{I^{tot}}_{e^-} = 60$ mA.

2.3 Observations of Weak-Strong Dynamics

Relative to the positrons, the electron beam has in general been more robust under the mutual interaction of the colliding beams. Operational experience shows that if the electron bunch current exceeds 0.4 mA or 1.8×10^{10} ppb, the positron beam experiences a reduction in beam lifetime with beams in collision. In a special study aimed at collisions with maximum single-bunch positron current, it was found that with up to 3 mA positrons and 0.4 mA electrons, the positron lifetime was significantly reduced while the electron beam lifetime was unaffected.

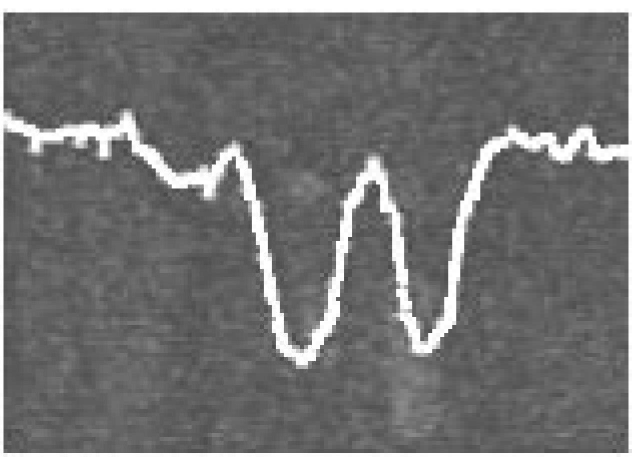

Figure 3: Measured positron beam current during a horizontal beam-beam scan with 1 colliding bunch. The electron current was constant at 0.2 mA. The full scales on the horizontal and vertical axes respectively are 8 minutes and 0.5 mA.

Shown in Fig. 3 is the positron beam current measured very early in colliding beam commissioning as the beams were scanned horizontally across one another while continually injecting positrons. When the beams were separated by about $\pm\Sigma_x$, the positron beam was nearly lost and further accumulation was difficult as evidenced by the two characteristic dips.

Another example of a strong-weak interaction is shown in Fig. 4. In the top plot the measured luminosity is depicted as the relative horizontal separation between the beams was stepped at an average rate of 16 μm per second in 50 μm steps. Again we observe pronounced dips at about $\pm\Sigma_x$. In this case, with both beams stored, the luminosity at about $\pm 2\Sigma_x$ was unchanged which is surprising since about 15% (middle plot) of the positron beam was lost at the onset of collisions.

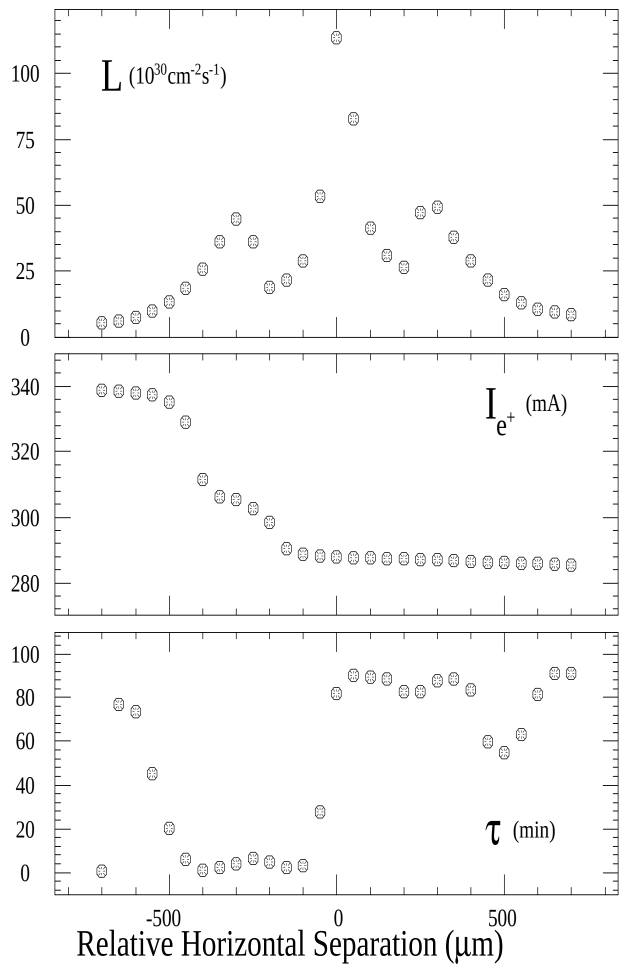

Figure 4: Measured luminosity (top), positron current (middle), and positron beam lifetime (bottom) during a horizontal beam-beam scan with 522 colliding bunches. The total electron current was 200 mA.

2.4 Observations of Strong-Strong Dynamics

Coherent centroid motion of colliding bunches has been observed for the special case in which the fractional vertical betatron tunes of the beams were made nearly equal. Shown in Fig. 5 are measured σ and π modes observed with a single bunch in collision, multi-bunch feedback off, and the vertical betatron tunes separated by $\delta\nu_y = 0.0002$ with $\delta\nu_x \approx 0.02$ and $\langle\nu_x\rangle - \langle\nu_y\rangle \approx 0.07$. With an I_{e^+}:I_{e^-} current ratio of 1:0.4 mA, the beam-beam parameter deduced from this measurement was unexpectedly small even taking into account a correction factor for non-rigid beams.

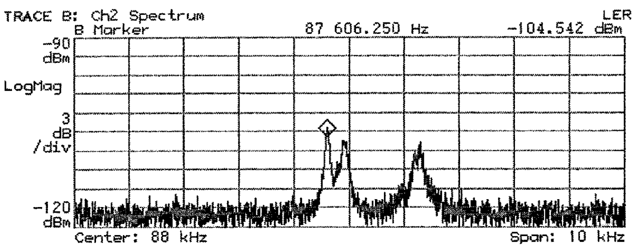

Figure 5: Measured coherent dipole modes. The peaks from left to right are the unperturbed positron vertical tune (measured before injecting electrons), the σ-mode, and the π-mode.

3 SINGLE BEAM, MULTIBUNCH BEAM STABILITY

With such closely spaced bunches, coupled-bunch instabilities, if not well controlled, have the potential of limiting high-current, multibunch performance. During single-beam commissioning studies, multibunch instabilities were observed in both accelerators. In the LER with well-separated bunches, with the exception of a singular higher-order longitudinal mode, both the transverse and longitudinal instability thresholds are reasonably consistent with expectation. In the HER however, while the beam is longitudinally stable with a threshold a factor of 2 higher than expected, transverse beam instabilities have been recently observed with thresholds considerably lower than expectation [6].

To date there is no single interpretation which explains all the single-beam measurements [7] in the HER. In addition, experiments performed in both rings with closely spaced bunches evidenced similar dynamics indicating possibly a common instability source. In this section we present a selection of recent measurements made to better characterize the multibunch beam dynamics. In the next section we present measurements which demonstrate the stabilizing influence that the beam-beam interaction has on transversely excited beams.

3.1 Experiments with large bunch separation

A measurement showing the instability threshold measured in the HER is shown in Fig. 6 for the case of an evenly spaced train of bunches, about 75 ns apart, with a 10 bunch gap at the end. Plotted on the vertical axes are the measured root mean square (rms) of the position distribution; i.e. the standard deviation of the beam centroid motion obtained from 100 measurements of the beam position on consecutive turns. From these data the threshold of the transverse instability was about 50 mA.

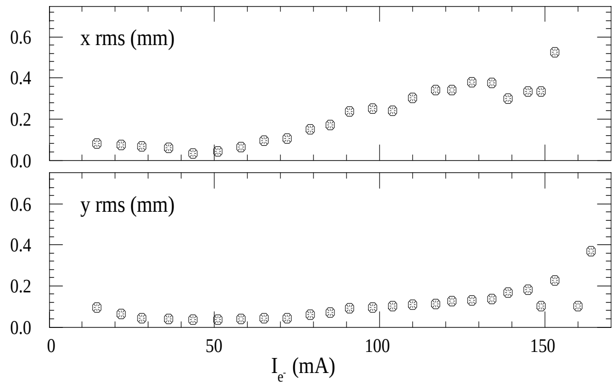

Figure 6: Threshold measurement in the electron ring with transverse feedback off in the horizontal (top) and vertical (bottom) planes.

In a separate set of measurements [7] taken using the multiturn, multibunch data acquisition capabilities of the longitudinal feedback system to record transverse motion [5], the characteristic frequency with this fill pattern was diagnosed as being primarily mode-0 motion with a growth rate of about 100 ms^{-1} at 100 mA.

3.2 Experiments with small bunch separation

Multi-bunch beam dynamics observed with short bunch trains may or may not be important with the design PEP-II fill pattern. The two filling patterns do, however, share an every-other-bucket fill sequence (i.e. 4.2 ns bunch spacing), and high single-bunch intensities. Multibunch beam instabilities with bunch trains were first noted in the electron accelerator as an inability to inject sequential high current bunches with (about 1 mA compared to the design single-bunch beam current of 0.45 mA) with the nominal interbunch spacing and transverse feedback turned off. Shown in Fig. 7 are measurements from the HER of the charge along the train for the indicated total current obtained after sequential-pulse filling. Interestingly, the same current distribution resulted after filling the train uniformly and then turning off the horizontal feedback loop.

To better understand the cause of beam loss, beam position monitors (BPMs) were used to measure the transverse motion for selected bunches. In this measurement the beam was first injected to 1 mA per bunch in a 50 bunch train with feedback on. The vertical feedback loop was then opened. The data acquisition was then synchronized to acquire data while opening the horizontal feedback loop. To improve the probability of time-overlap between these events, the position detectors were sampled every 100th or 200th turn.

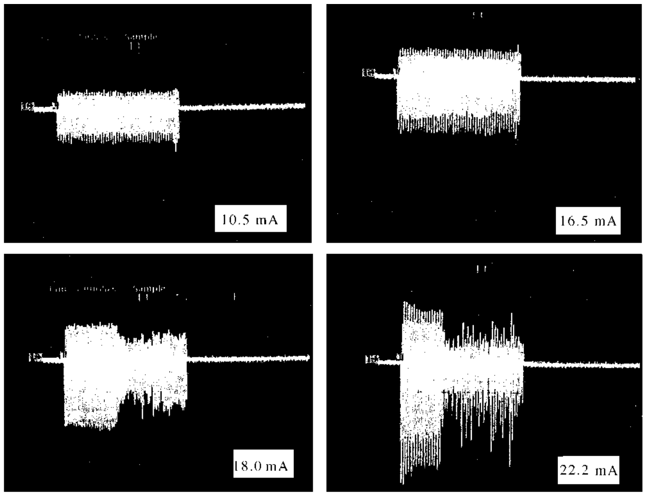

Figure 7: Bunch intensity monitor data with a 100-bunch train with the nominal bunch spacing and transverse multi-bunch feedback turned off.

These data are shown in Fig. 8. The first column shows the measurements with the BPMs gated[1] on a low-current bunch. The second column shows measurements gated on a bunch for which there was more current in the final state. While the horizontal motion is significantly larger in amplitude, when the data are normalized to the beam size, the vertical motion was observed to dominate.

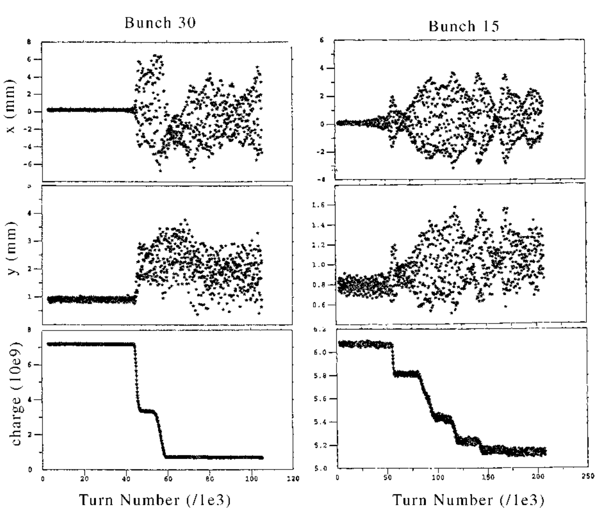

Figure 8: Transverse motion of selected bunches in a 50 bunch train recorded as transverse feedback was turned off. Plotted are the measured horizontal (top) and vertical (middle) beam centroid positions, and the beam intensity (bottom) measured in the HER.

With a 100-bunch train and 4.2 ns bunch spacing, the transverse position rms along the train was measured for different beam currents as shown in Fig. 9. These data from the HER show clearly the self-excitation of the beam moving towards the front of the train as the beam current was increased. These data also support previous results indicating that the excitations are preceeded by motion in the horizontal plane.

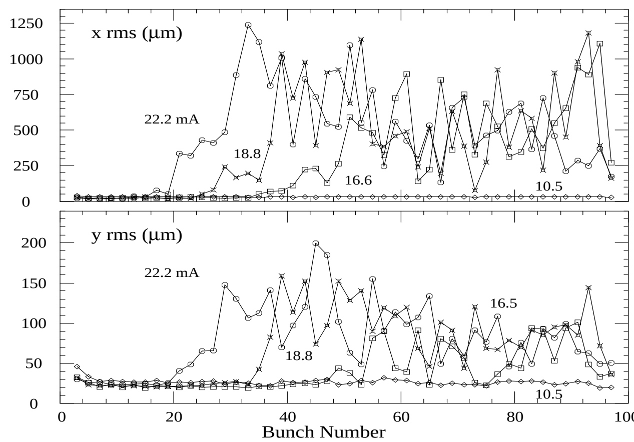

Figure 9: Growth in distribution of horizontal (top) and vertical (bottom) bunch centroid motion along a 100-bunch train with bunches spaced by two buckets.

As mentioned previously, multibunch beam dynamics with bunch trains in the low-energy ring evidenced similar features of beam loss along the fill pattern [7].

4 MULTIBUNCH BEAM STABILITY WITH BEAMS IN COLLISION

During early commissioning with high-current multibunch beams it was found that the required gains of the transverse feedback system could be substantially reduced with beams in collision. Two experiments were performed to better quantify this effect. For these measurements the current distribution consisted of 786 bunches spaced at twice the nominal bunch separation with a 10% gap in the fill pattern.

4.1 Experimental Data

In the first measurement the transverse feedback gain required to damp the measured 0-mode excitation was measured as function of electron beam current. The data are shown in Fig. 10. The single-beam measurements show that with 150 mA electron beam current about 15 dB of gain was needed to damp the horizontal centroid motion to the -120 dB noise floor of the spectrum analyzer. In the vertical plane, with a maximum relative gain of 30 dB, above 150 mA there was insufficient gain to fully damp the coherent motion.

With the beams nominally colliding head-on, the measurement was repeated as indicated using crosses in Fig. 10. With these beam currents, it was possible to turn

[1] The finite bandwidth of the BPM electronics (around 20 MHz) dilutes the single-bunch measurement by including about ± 10 buckets (or ± 5 bunches in the every-other-bucket fill pattern) centered on the bunch of interest.

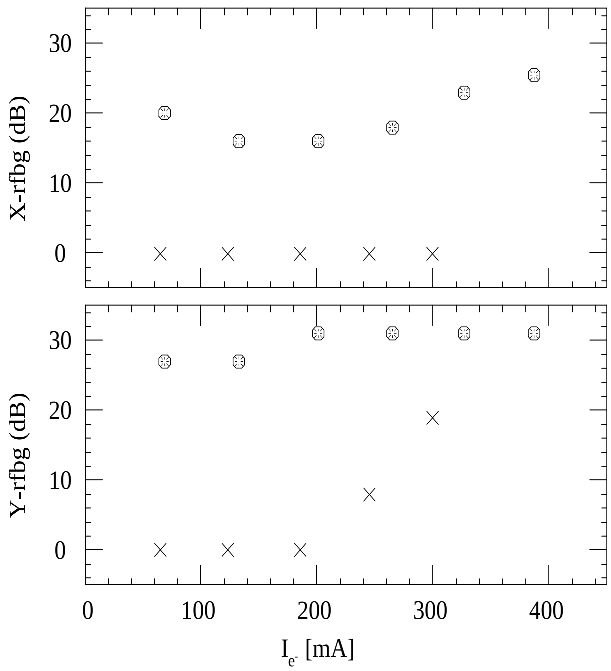

Figure 10: Required feedback gain (rfbg) versus electron beam current with beams in (crosses) and out (circles) of collision in the horizontal (top) and vertical (bottom) planes. In this measurement the total positron beam current was fixed at 0.5 A and there were 786 colliding bunches.

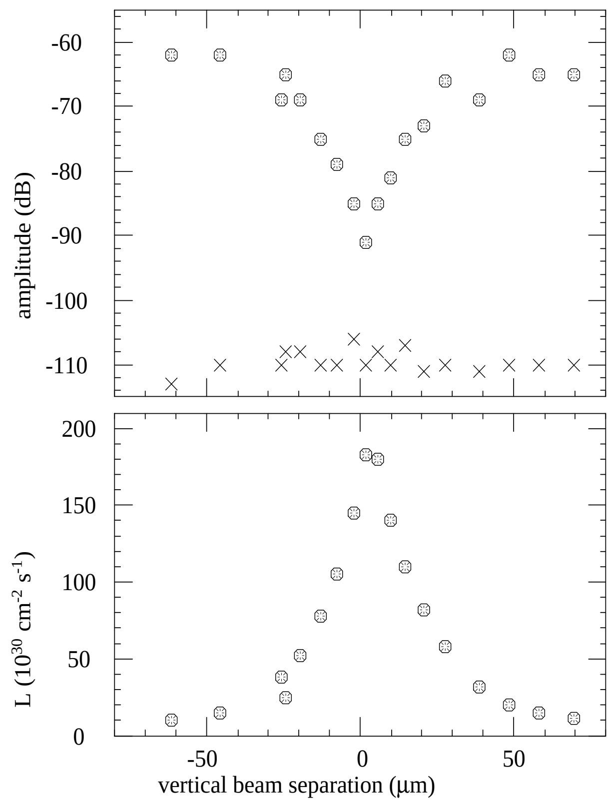

Figure 11: Measured horizontal (crosses) and vertical (circles) instability amplitude (top), and luminosity (bottom) versus relative separation of the colliding electron and positron beams. In this measurement the total currents of the 786 colliding electron and positron beams was respectively 315 mA and 450 mA.

off entirely the horizontal multibunch feedback loop. In the vertical plane, the beam-beam interaction damped the residual motion by 30 dB. The apparent increase in gain required at high beam currents may have resulted from a relative beam separation of about one to two Σ_y (see below).

In a separate measurement, the 0-mode instability amplitude was measured as a function of the vertical separation between the beams as shown in Fig. 11 (top) with transverse feedback off. Under these conditions with relative separations of up to about $5\,\Sigma_y$ the horizontal motion of the beam remained fully damped. Comparing with the simultaneously measured luminosity (bottom) reveals that the residual motion was smallest with the beams best centered vertically.

4.2 Quantitative Analysis

We interpret the observed behavior as a consequence of the nonlinearities in the beam-beam interaction; recalling that the beam-beam tune shift is amplitude dependent (being larger the smaller the amplitude of the particle motion), the beam-beam interaction introduces an increased tune spread within the beam. This increased tune spread allows for more Landau damping.

Notice the distinct difference in dynamics of the last two figures. In Fig. 10 the beams were nominally maintained in head-on collision. In Fig. 11 the relative separation between the beams was varied. For head-on collisions, the resulting tune shifts may be easily expressed by averaging the beam-beam potential over betatron phase. From reference [8], the horizontal ($\Delta\nu_x$) and vertical ($\Delta\nu_y$) tune shifts are

$$\begin{aligned} \frac{\Delta\nu_x}{\xi\left(\frac{1+\frac{1}{a}}{2}\right)} &= \int_0^\infty \frac{Z_1\left(\frac{\alpha_x}{1+u}\right) Z_2\left(\frac{\alpha_y}{1+\frac{u}{a^2}}\right)}{(1+u)^{\frac{3}{2}}(1+\frac{u}{a^2})^{\frac{1}{2}}} \mathrm{d}u \\ \frac{\Delta\nu_y}{\xi\left(\frac{1+a}{2}\right)} &= \int_0^\infty \frac{Z_1\left(\frac{\alpha_x}{1+a^2 u}\right) Z_2\left(\frac{\alpha_y}{1+u}\right)}{(1+u)^{\frac{3}{2}}(1+a^2 u)^{\frac{1}{2}}} \mathrm{d}u, \end{aligned} \qquad (1)$$

where

$$\begin{aligned} Z_1(x) &= e^{-x}\left[I_0(x) - I_1(x)\right] \\ Z_2(x) &= e^{-x} I_0(x). \end{aligned} \qquad (2)$$

Here $\sqrt{\alpha_x}$ and $\sqrt{\alpha_y}$ denote the particle amplitudes normalized by the beam sizes, $a = \Sigma_y/\Sigma_x$ is the beam aspect ratio (assuming matched IP beam sizes), and I_0 and I_1 are the modified Bessel functions. Using these expressions, with the measured aspect ratio of $a = 0.06$, we find that for large vertical separation (in units of σ_y), the horizontal tune shift greatly exceeds the vertical tune shift; at $10\sigma_y$ for example, $\Delta\nu_x \approx 10\Delta\nu_y$. The measurements in Fig. 10 are therefore not surprising since particles displaced to large vertical amplitude still experience strong horizontal beam-beam forces.

Being able to turn off the horizontal feedback loop with beams in collision indicates that the tune spread generated by the beam-beam interaction was large compared to the instability growth rate. Taking as an approximate measure of the Landau damping rate ξf_{rev} and the larger of the electron and positron vertical tune shifts for the data of Fig. 11, the imperfect damping of the multibunch instability during head-on collisions suggests an instability growth time less than $(\xi f_{rev})^{-1} \approx 0.5$ ms with $\xi_{y,e^+} = 0.015$. With multibunch feedback designed [9] to damp up to three times the predicted resitive wall instability growth rate of 0.3 ms^{-1}, it is expected that with this high-current, multibunch fill pattern, any residual motion may not be fully suppressed. In the future we hope to make similar measurements both with and without multibunch feedback to better characterize the growth time of observed multibunch instabilities.

It is also worth pointing out the apparent absence of the coherent π-mode in the data presented. We have come to understand this observation as a result [10] of unequal fractional betatron tunes. With unequal tunes, the π-mode frequency is shifted into the continuum where Landau damping takes place [11].

5 CONCLUSION AND OUTLOOK

Colliding beam commissioning at PEP-II has been a fruitful and rewarding experience with encouraging prospects for multibunch, high current collisions with BABAR; the measured luminosity, listed chronologically in Table 2, has increased steadily with each colliding beam experiment. The increase in specific luminosity is seen to result from minimization of the vertical spot size. This together with increased beam currents led to steady gains in total luminosity.

An illustrative current scan is shown in Fig. 12. In this measurement 786 bunches with twice the design bunch spacing were in collision. Interestingly, the highest three data points were obtained after raising the electron vertical tune very slightly (less that 0.005) to be nearly equal to that of the positrons. The deviation from the design luminosity probably results from an increased vertical beam size which was measured at this time to be about twice nominal. Further correction of the beam optics (including coupling and dispersion) should allow the design vertical spot size at the IP to be attained. For increased total luminosity, the beam currents will be raised towards design values as vacuum conditioning and detector backgrounds allow.

To date, there has been no direct evidence of reduced luminosity due to transverse beam instabilities at PEP-II. For most current distributions, the strong transverse, coupled-bunch motion has been successfully damped by the transverse bunch-by-bunch feedback system. Moreover, even without feedback, the beam-beam interaction was qualitatively observed to stabilize such motion. Surprisingly, the increase in Landau damping, resulting from the betatron tune spread induced by the beam-beam collisions, exceeds the amount of damping offered by the high-gain multibunch feedback system. Whether or not future colliders like the LHC could potentially benefit from similar dynamics, while very likely, is an open question.

Date	N_c	I_{e^-}	I_{e^+}	Σ_x	Σ_y	L	L_{sp}
11/98	1	0.6	1.3	209	40	0.003	0.55
11/98	11	6.6	14.3	209	40	0.027	0.55
12/98	261	84	260	320	14	0.8	1.02
2/99	786	354	680	220	12	5.2	1.71
design	1658	750	2140	220	6.6	30	3.11

Table 2: Peak luminosity history showing progressive improvements with each colliding beam run. The units are I(mA), Σ (μm), L($\times 10^{32}$ cm^{-2}s^{-1}), and L_{sp} ($\times 10^{30}$cm^{-2}s^{-1}mA^{-2}).

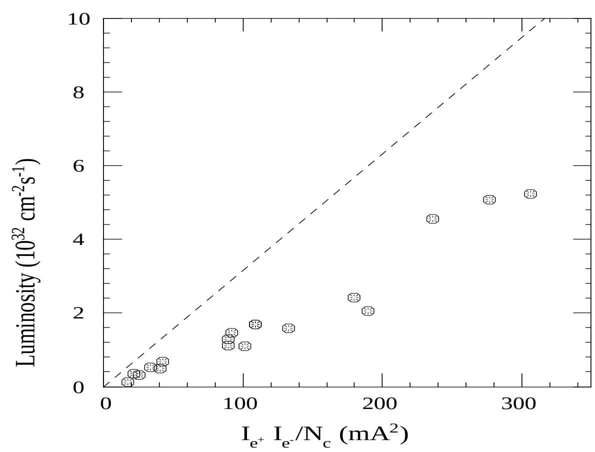

Figure 12: Measured luminosity as a function of the product of the beam currents scaled by the number of colliding bunches. These data were taken with 786 bunches and positron/electron currents in the range of 275-720/60-350 mA respectively. The dashed line shows the expectation assuming design parameters.

Acknowledgements

We gratefully acknowledge the much appreciated efforts of the SLAC operations and technical support groups. In addition we thank our commissioning collaborators including W. Barry, J. Byrd, J. Corlett, P. Corredoura, F.J. Decker, M. Donald, S. Ecklund, R. Erickson, T. Fieguth, J. Fox, S. Heifets, L. Hendrickson, R. Iverson, P. Krejcik, A. Kulikov, D. Li, T. Mattison, H. Nishimura, N. Phinney, S. Prabhakar, R. Rimmer, M. Stanek, D. Teytelman, R. Tighe, J. Turner, S. Zholents, F. Zimmermann, and B. Zotter. Last but not least we would like to thank A. Chao and F. Willeke for insightful discussions while preparing this report.

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