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Coupled-Bunch Instability Measurements at PEP-II (Oct-Dec, 1998) [1]

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1 Introduction

Coupled-bunch instabilities have been observed in the PEP-II high energy electron ring (HER) and in the low energy positron ring (LER). To better characterize the beam motion, new diagnostics were developed and improvements to existing diagnostics were made. The relative sensitivies of the measurement methods were evaluated and systematic effects were carefully analyzed and subsequently reduced. The studies were occassionally hampered by day-to-day irreproducibility; for example, in the HER, sometimes two-bunch instabilities were observed while in the LER an occassional single-bunch instability was noted. As a consequence, absolute measurements of the instabilities' properties proved difficult, however relative changes were successfully studied. Measurements were made of instability thresholds, characteristic frequencies, and relative growth rates. These observables were found to depend strongly on various beam properties including fill pattern, single bunch current, and total beam current.

Certain features of the beam instabilities were dominant in the measurements. For example, strong horizontal excitations were identified and were reproducible for the case of short bunch trains in the HER. Interestingly, measurements in the LER with short bunch trains evidenced similar features indicating a possible common source. With bunch trains, while horizontal motion was prevalent, when normalized to the beam size, motion in the vertical plane was found to be equally significant with regards to the potential impact on collider luminosity. To date, it has not been determined whether the stability issues observed with bunch trains may be relevant for more evenly spaced beam current distributions as in the design fill pattern. Fortunately, in both accelerators, the beam was observed to be more stable with more uniform bunch fills and at modest single-bunch beam currents.

In this report is presented a summary of data acquired in both the electron and positron rings during the October-December 1998 commissioning period. Properties of the two accelerators and symbol definitions are given in Table I. In the main text, the data are classified in terms of bunch fill pattern; cross references to specific experiments are given in appendix A. An overview of theoretical models and simulations is given in references [1], [2], and [3]. Instability measurements made during previous commissioning runs are given in references [4], [5], [6], [7], and [8].

[1] Work supported in parts by the U.S. Department of Energy, contract DE-AC03-76SF00515.

Parameter	Symbol	HER	LER
Beam Energy	E (GeV)	8.973	3.119
Circumference	C (m)	2199.3	2199.3
RF Frequency	f_{rf} (MHz)	476	476
Revolution Frequency	f_{rev} (kHz)	136.3	136.3
Max Beam Current	I (mA)	325	400
Momentum Compaction	α	0.00241	0.00123
Horizontal Tune	ν_x (range/typical)	0.58 - 0.72, 0.62	0.54 - 0.57, 0.54
Vertical Tune	ν_y (range/typical)	0.62 - 0.64, 0.64	0.64
Synchrotron Tune (at zero current)	$\nu_{s,0}$	0.0337	0.0252/0.0253
Total Cavity Voltage	V_c (MV)	8.4	3.0
Radiation Loss (with/without wiggler)	U_0 (MeV)	3.55	0.759/0.662
Synchronous Phase (at zero current)	ϕ_s (rel. to rf crest)	65	75/77

Table 1: Selected PEPII accelerator parameters of the Oct-Dec 1998 commissioning period.

2 Diagnostics

Coupled-bunch instabilities are well described by the thresholds, characteristic frequencies, and the growth rates. With regards to threshold measurements, the order of increasing sensitivity was determined to be beam loss seen on the bunch current monitor, errant motion observed using the synchrotron light monitor, the root mean square (rms) beam position measured using buffered data acquisition, observation of self-excited lines on a spectrum analyzer, and beam motion detected using the bunch-by-bunch data acquisition systems. Characteristic frequencies were determined using both the bunch-by-bunch acquistion and, based on the identification of prevalent low-order modes, the spectrum analyzer. Growth rate measurements were documented only by the bunch-by-bunch feedback systems. For low growth rate modes, a spectrum analyzer used with zero span also proved useful.

Many improvements were made during this run in characterizing beam instabilities. Improved isolation of the fast switch used for gating on and of the transverse feedback was implemented and measurement reproducibility was demonstrated using an improved measurement procedure. To eliminate systematic effects arising from '21 Hz' (aka 130 Hz) motion and errant 'flier' pulses, beam centroid measurements using the beam position monitors were processed offline. New diagnostics tools developed include the use of ion clearing electrodes, spectrum analyzer gating to allow for bunch-by-bunch tune shift measurements, and the development of acquisition software for beam transfer function measurements.

3 High Energy Ring Measurements

The data presented below are sorted in terms of bunch fill pattern including measurements with a single bunch, two equidistant bunches, and other bunch fill patterns. Except where noted, the data were typically acquired with a bias towards equal bunch spacing for which the harmonic number was evenly divisible by an integer; that is for M bunches (spaced by N buckets) of 1(3492), 2(1746), 3(1164), 4(873), 6(582), 9(388), 12(291), 18(194), 36(97), and vice versa (M and N interchanged). Filling patterns with N odd were avoided. Measurements obtained with bunch trains are also presented. The design fill pattern for PEP-II is 1746 bunches (spaced by 2 buckets) minus a 5% gap.

3.1 Few Bunch Uniform Fill Patterns

No single-bunch beam instabilities were observed using the readily available spectrum analyzer up to the administrative single-bunch current limit of 2 mA. Using the bunch-by-bunch acquisition system with a reduced down-sampling factor to allow for longer time records, driven 60 Hz was observed[2] in the horizontal plane with a single, 0.6 mA bunch without residual motion vertically. This was later determined to be instrumental. Taken together, these single-bunch data imply the absence of any driven transverse motion in the HER at low beam current.

Commissioning of beam transfer function measurement[3] hardware was also carried out with a single bunch. The data may have been hampered by bad isolation between the applied excitation and the detector. This 'background' might be subtracted offline.

The betatron tune spread was carefully measured using an externally applied excitation. The data[4] are shown in Fig. 1 which shows an increase in the horizontal tune ν_x spread relative to the single bunch tune spread. With two bunches, excitation at the the vertical and synchrotron tunes was also more evident.

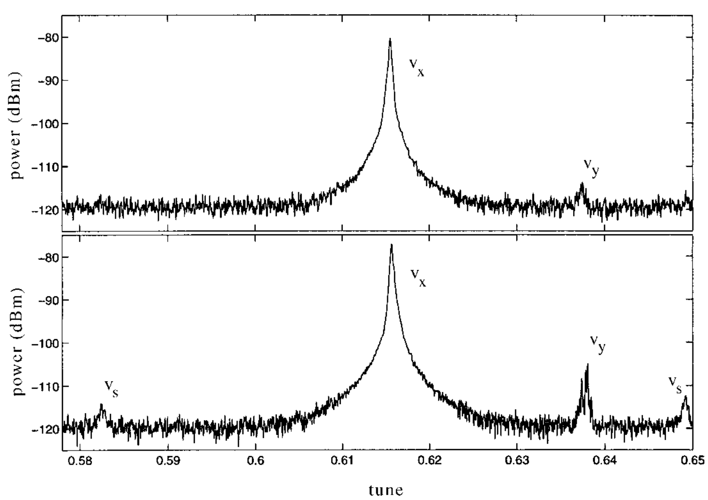

Figure 1: Comparison of betatron tune spreads measured using horizontal position electrodes with a single bunch (top) and two bunches (bottom). The total current was 1 mA in both cases. The spectrum analyzer was not gated.

[2]log 19, pp. 116-119 (11/19/98), measurements by W. Barry, J. Fox, M. Minty, S. Prabhakar, D. Teytelman
[3]log 21, pp. 76-79, 103-115 (11/28-30/98), measurements by A. Fisher, M. Placidi, U. Wienands, B. Zotter
[4]log 19, pp. 14-15 (11/13/98), measurements by Y. Cai, U. Wienands

For comparison with Fig. 1 is shown[5] in Fig. 2 the horizontal spectrum with 4 and 9, respectively, equidistant bunches at a total current of 1 mA. As the number of bunches was increased, an increased sensitivity to the betatron coupling resonance and possibly to sychro-betatron resonances was observed.

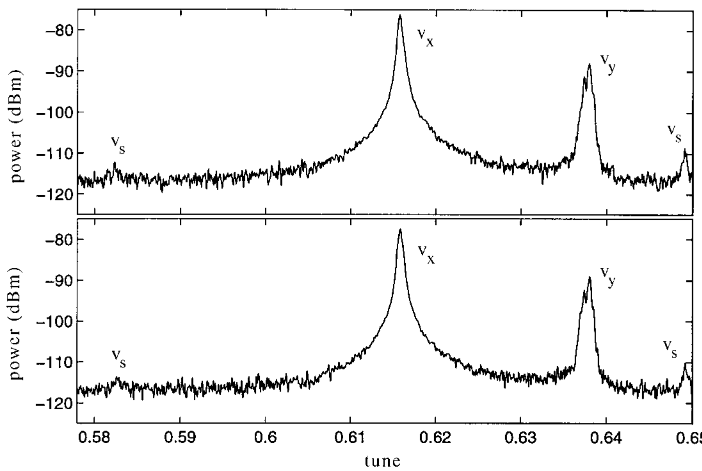

Figure 2: Comparison of betatron tune spreads measured using horizontal position electrodes with 4 (top) and 9 (bottom) equidistant bunches. The total current was 1 mA in both cases. The spectrum analyzer was not gated.

3.2 18 Bunch, 18-1, and 18-2 Fill Patterns

For the bunch-by-bunch data acquisition, an 18 bunch evenly spaced beam current distribution was initially chosen based on this fill patterns' reasonably high (tens of mA) threshold and the relative speed of online analysis of uniform fills. An example of vertical beam motion recorded[6] using the data acquisition capabilities of the longitudinal feedback system is given in Fig. 3. The betatron tunes were $\nu_x = 0.618$ and $\nu_y = 0.635$. With this fill pattern, mode-1 was observed to increase nonexponentially[7]. Using previously applied [4]-[6] techniques to evaluate the growth rate, the corresponding growth rate determined online for this mode-1 instability was about 0.85 ms^{-1}. The measurements also revealed a shift in the excited modes with increasing current up to the maximum current sampled of about 30 mA. In addition, as had been previously observed [4],[5] the modes were observed to saturate. The measured threshold with this uniform fill was about 5 mA. With 1 bunch missing, in the so-called '18-1' fill pattern, the threshold was found to increase slightly to 10 to 15 mA.

The following day the measurements were repeated after the interaction region optics had been modified for increased beta function at the interaction point β^*. This 'relaxed lattice' consisted of a two-fold increase in $\beta_y{}^*$ while the beta function elsewhere in the interaction

[5]log 19, p. 16 (11/13/98), measurements by Y. Cai, U. Wienands

[6]log 17, pp. 123-125 (11/3/98), measurements by J. Fox, M. Minty, D. Teytelman

[7]note that the frequency associated with a given mode is known modulo the rf frequency

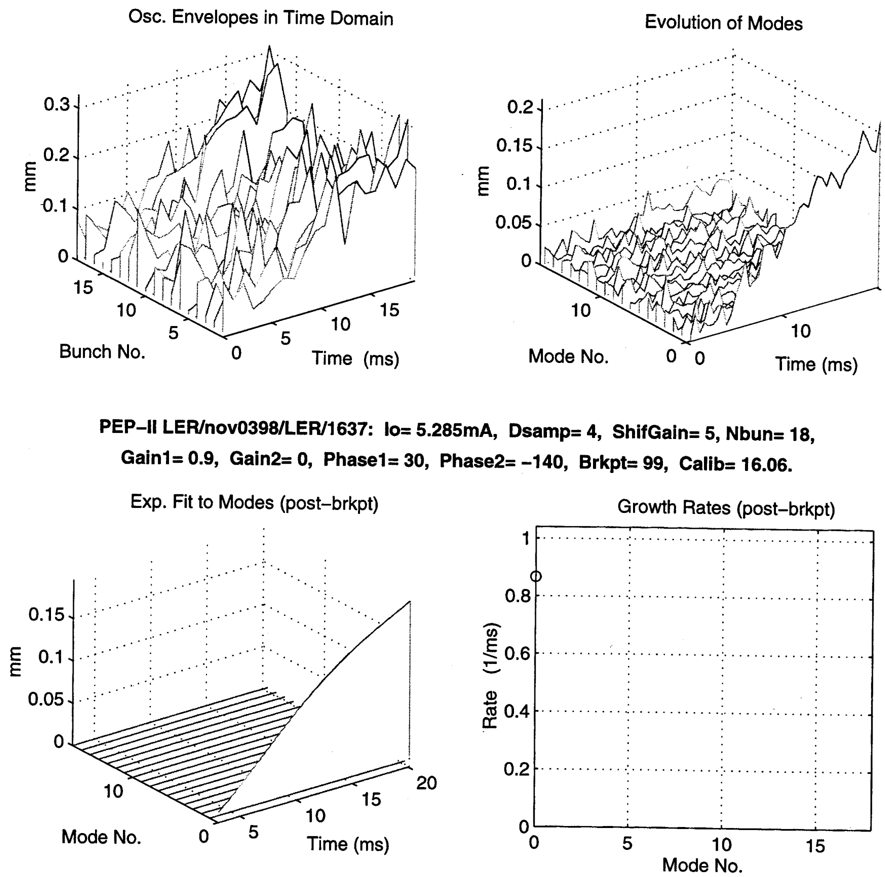

Figure 3: Modal analysis of vertical motion with an 18 bunch uniform fill pattern showing raw data (top left), frequency domain analysis expressed in terms of excited modes (top right), analyzed fit to excited modes (bottom left), and growth rate determined from the analyzed fit (bottom right). The total current was 5 mA and transverse feedback was turned off at about 2 ms in these plots.

region straight was reduced by about a factor of two. The betatron tunes were moved slightly to $\nu_x = 0.629$ and $\nu_y = 0.581$ to avoid complications from the nearby betatron coupling resonance. The measurement with an 18-bunch uniform fill of 10 mA did not reproduce as evidenced by a change in amplitude at saturation of a given excited mode. Measurement-to-measurement reproducibility studies ensued and a pre-measurement setup procedure was developed consisting of three steps. First, the dc beam position offsets at the transverse feedback pickups were zeroed in order to avoid possible electronic saturation which could occur at high feedback gain. Second it was found necessary to control the beam using feedback in the orthogonal plane to achieve reproducibility in the plane of interest. Third, poor isolation in the high-speed switch used to gate on and off the transverse feedback was diagnosed. To overcome this difficulty, a variable output function generator was used to establish perfect switching as determined by noting the betatron amplitude using a spectrum analyzer with a span of zero while triggering the switch at a 1 Hz rate.

Consistent measurement-to-measurement reproducibility was demonstrated[8] as shown in Fig. 4. The plots show the transient growth of each detected mode as the current is increased with the uniform 18 bunch fill pattern. The plots are pre-selected based on the observation that the largest excited mode increased with increasing single bunch (and hence total) beam current. This behavior is shown explicitly[9] in Fig. 5. In this graph, the mean amplitude of the excited modes is shown versus mode number for different beam currents.

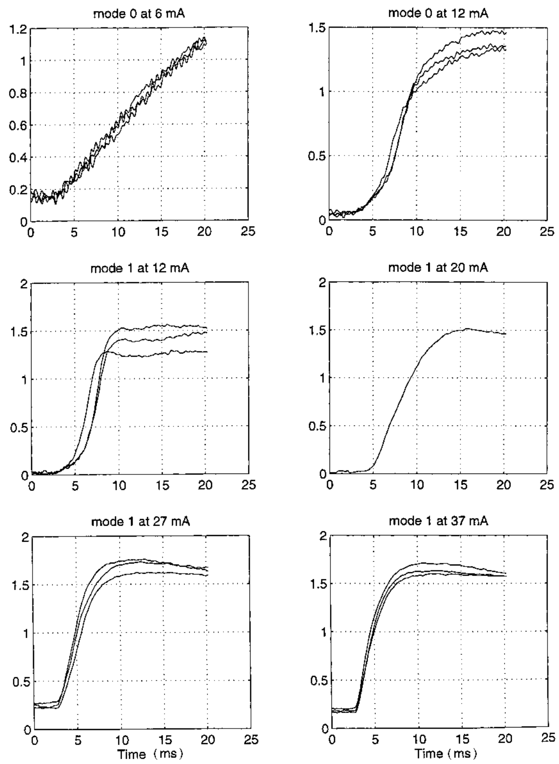

Figure 4: Mode saturation (in arbitrary units) of vertical motion in an 18 bunch uniform fill pattern demonstrating measurement-to-measurement reproducibility and growth rates of the indicated modes and total beam current.

Based on the acquired data it was unclear from growth-rate analysis whether the change in the interaction region beta-function strongly affected beam stability. With the relaxed lattice, the centroid of the observed characteristic frequencies was observed to shift upward by one mode. Data obtained in the 18-1 and 18-2 fill patterns indicated that, as with the nominal lattice, the instability threshold was somewhat higher with the missing bunch(es) present. In addition, the threshold with the 'relaxed' lattice seemed to increase slightly (by a maximum of ≈10 mA) relative to the nominal lattice.

In a separate measurement with the 18 bunch even fill pattern at 15 mA total beam current, the dependence on the temperature of the interaction region was studied[10]. In this case, the wa-

[8]log 17, pp. 136-140 (11/4/98), measurements by M. Minty, S. Prabhakar, D. Teytelman

[9]log 17, pp. 136-140 (11/4/98), measurements by M. Minty, S. Prabhakar, D. Teytelman

[10]log 18, pp. 129-137 (11/11/98), measurements by J. Fox, D. Manley, M. Minty, S. Prabhakar, D. Teytelman

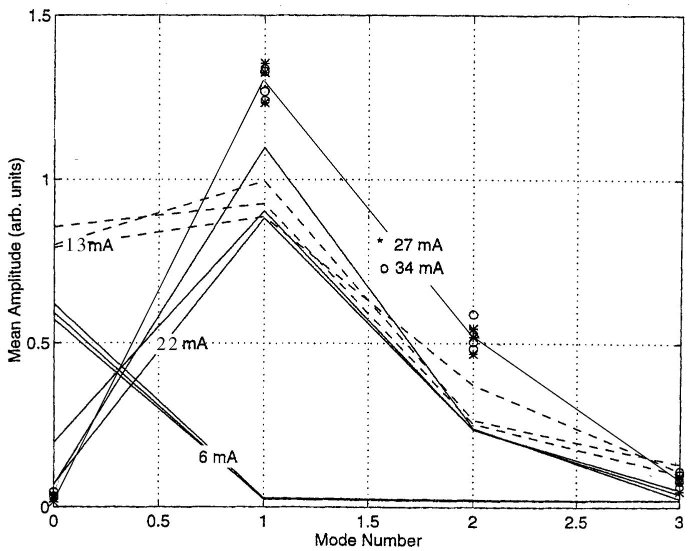

Figure 5: Vertical amplitude at saturation (arbitrary units) versus mode number with an 18 bunch uniform fill and 'relaxed' lattice.

ter temperature was lowered producing a 4-6 degree Fahrenheit change in magnet temperatures. No discernable change was detected in the vertical growth rates or modal patterns.

At this time the mode evolution was evaluated[11] as shown in Fig. 6 at the saturated amplitude. Detecting over longer time scales, the mode evolution was observed to be oscillatory. On the same day, using the 18 bunch even fill pattern, the horizontal motion was recorded for the first time. The spectrum revealed mode-0 excitation with a growth rate of 0.05 ms^{-1} at 18.6 mA.

Reproducible characteristic frequency and growth rate measurements proved to be challenging over time periods spanning more than a day. With the 18 bunch uniform fill, subsequent measurements[12] revealed now an absence of frequency shift in the vertical plane with increased beam current. An example of data acquired at this time is given in Fig. 7 which shows 3 separate measurements of the mode-0 transient response. The different measurements correspond to different transverse feedback gains as evidenced by the change in residual amplitude before feedback was switched off. With betatron tunes of $\nu_x = 0.628$ and $\nu_y = 0.598$, only mode-0 was observed to be unstable with a low threshold of less than 5 mA.

Later measurements[13] showed even higher growth rates (0.023 ms^{-1}) in multiple (two or three) modes. The apparant lack of reproducibility seemed to be caused by changes in the beam conditions. Subsequently it was discovered that the beam orbit was changing both with time (at low current) and as a function of current [9]. Whether or not this explains the lack of day-to-day reproducibility has yet to be determined.

[11] log 18, p. 137 (11/11/98) measurements by J. Fox, D. Manley, M. Minty, S. Prabhakar, D. Teytelman
[12] log 19, pp. 116-119 (11/19/98), measurements by W. Barry, J. Fox, M. Minty, S. Prabhakar, D. Teytelman
[13] log 20, pp. 44-49 (11/22/98), measurements by S. Prabhakar, D. Teytelman, U. Wienands

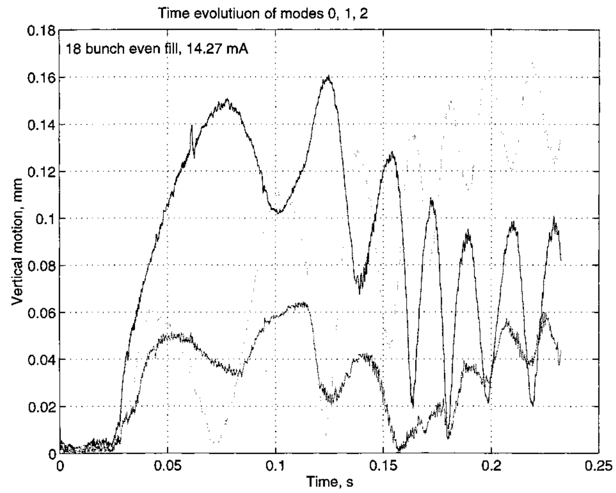

Figure 6: Time evolution of first 3 vertical modes with an 18 bunch uniformly filled current distribution. Transverse feedback was turned off at about 0.03 s in this plot.

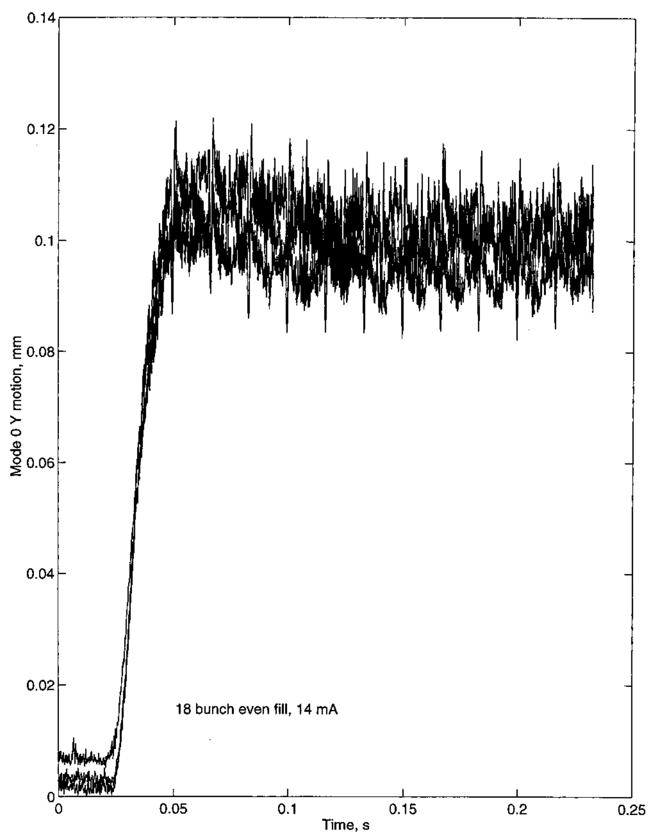

Figure 7: Time evolution of mode-0 vertical mode with an 18 bunch uniformly filled current distribution. The three different curves correspond to three different transverse feedback gains. Transverse feedback was turned off at about 0.025 s in this plot.

3.3 36 Bunch Even Fill Pattern

Spectrum analyzer data were taken in both transverse planes with a 36 bunch uniform fill pattern on two separate occassions as a further test of the relaxed lattice configuration. The data[14] are shown versus current in Fig. 8. The relaxed lattice data have tunes equal to the design tunes. While in both cases the spectra are rich in harmonic content, based on these data, there seemed to be little significant change in the instability threshold and saturated amplitude comparing the two different lattices.

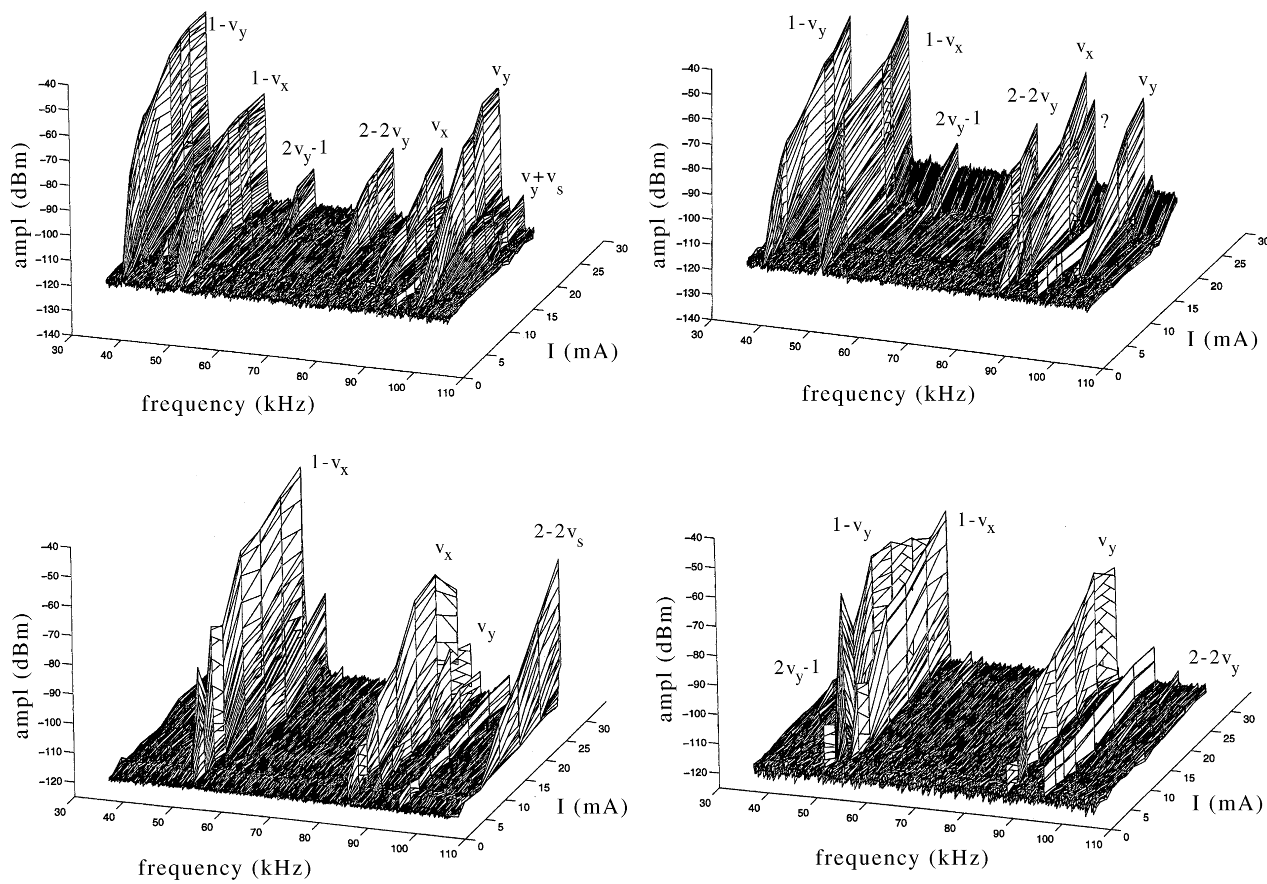

Figure 8: Spectrum analyzer data taken with a 36 bunch uniform fill pattern for the initial and relaxed lattices. The columns show the spectra for data taken in the horizontal and vertical planes respectively. The top two plots have the 'pre-design' lattice used early in the run for which $\nu_x = 0.633$ and $\nu_y = 0.721$. The lower two plots taken with the relaxed lattice have $\nu_x = 0.615$ and $\nu_y = 0.635$. The line near 94.5 kHz is instrumental. The spectrum analyzer was not gated.

[14] log 16, p. 123 (10/29/98), measurements by M. Minty; log 18, pp. 52 and 57 (11/7/98), measurements by M. Minty

3.4 97 Bunch Even Fill Pattern

A fast method for measuring instability thresholds was developed using the beam position monitors (BPMs) and buffered data acquisition. Typically 1024 turn-by-turn beam position measurements were taken and the rms (i.e. standard deviation of the beam centroid distribution) was determined offline after cuts on an errant '21 Hz' (aka 130 Hz) systematic problem (inherent in the signal processing electronics) and unphysical 'flier' pulses

Using this technique the instability threshold was measured[15] as shown in Fig. 9 with a '97-10 fill pattern' consisting of 97 equally spaced bunches with 10 consecutive bunches absent[16] with and without transverse feedback. Here, and in all subsequent measurements, unless otherwise noted, the BPMs were timed to sample bucket zero (i.e. the first bunch injected which was typically at the head of the bunch 'train'). From these data, the threshold of the transverse instability was surprisingly low and preceeded by increased motion in the horizontal plane.

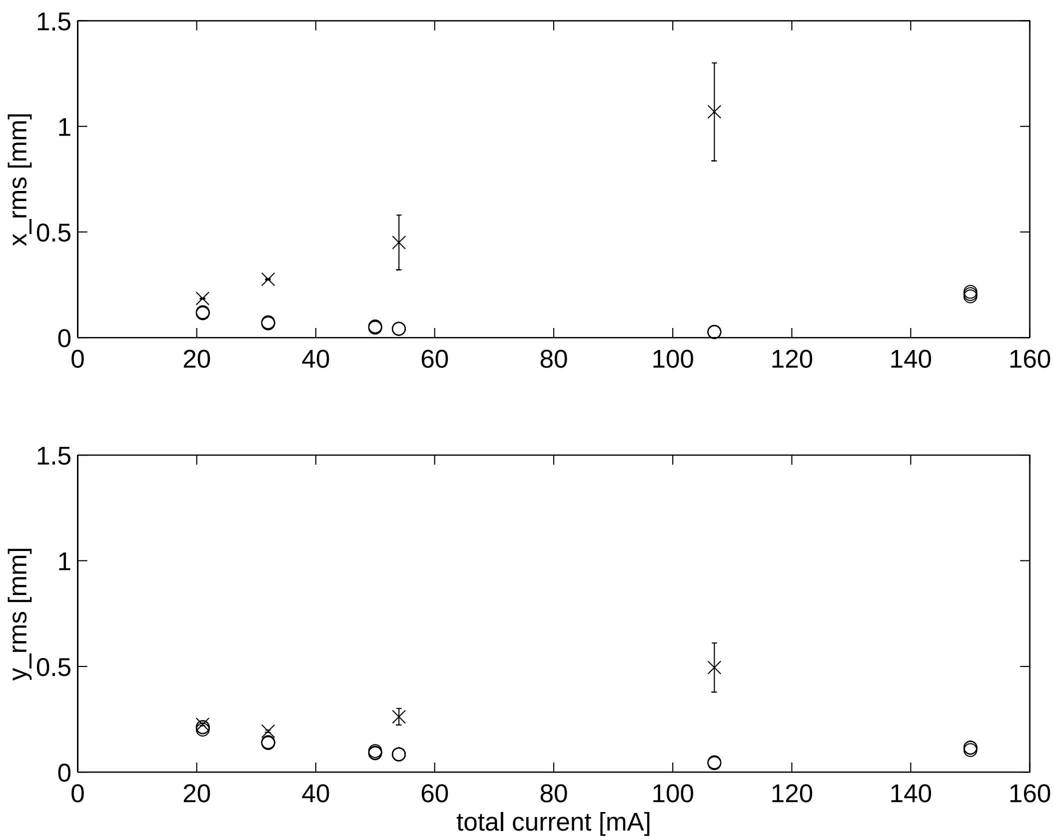

Figure 9: Threshold measurement with a 97-10 bunch fill pattern with feedback off (crosses) and on (circles). The single bunch rms was measured to be 25 μm in x and 28 μm in y.

[15] log 19, pp. 121 and 127 (11/19/98), measurements by M. Minty

[16] note that absolute rms (after filtering for systematic 130 Hz and flier pulses) was found subsequently to depend on the BPM calibration; improper calibration could result in an increase (beyond the BPM resolution) in the measured rms

In a separate set of measurements taken on the same day[17] in the same 97-10 fill pattern, the vertical spectrum was observed to be 'quiet' up to 100 mA. The horizontal motion was also measured and showed primarily mode-0 motion with a growth rate of about 100 ms^{-1} at 100 mA.

Using the 97-10 fill pattern, at modest beam current of about 30 mA for which the beam was relatively stable (see Fig. 9), an experiment was undertaken to test for a possible localized transverse impedance. The procedure consisted of making a global orbit oscillation and measuring, using buffered data acquisition, the rms of the transverse beam motion. A null result would have indicated the absence of such an impedance. A positive result might have prompted a more time consuming effort to localize its source using either closed bumps or by performing a binary search.

Shown in Fig. 10 are the measured[18] rms (i.e. standard deviation of the beam centroid distribution) versus amplitude of the transverse orbit oscillation after offline cuts on BPM systematics and flier pulses. Three different correctors were used to fully span the 60 degree lattice. The full scale on the applied perturbation (horizontal axis) ranged from ± 5 mm as measured independently using multiple BPMs. The order of the data taken was nonsequential; that is, from left to right on each graph, the time sequence of the data was 2-4-1-5-3 for better assurance against systematic changes (in the beam orbit, for example). From Fig. 10 there was no change in the rms of the beam with induced horizontal orbit oscillations.

Similar scans taken with vertical closed orbit distortions are shown[19] in Fig. 11. Of the three betatron phases tested, one phase showed a significant change (bottom plot) while the intermediate phase (middle plot) hinted at an orbit dependence to the transverse instability.

In an ensuing experiment[20], growth rates were measured using the bunch-by-bunch feedback system at the nominal orbit and at orbits deemed errant by the previous measurements (see Fig. 11). The data are shown for three different vertical orbits in Fig. 12. As the bump amplitude was increased from nominal (top) to larger amplitude (bottom plots), the transient growth was observed to vary from being flat, to exponential, to concave down. These data support the previously acquired data suggesting the possible presence of a significant transverse impedance. Indeed, it had been noted earlier[21], that the proximity to the injection septum channel strongly affected the ability to store high current beams (see section 3.6).

Data acquired using a spectrum analyzer and the 97-10 fill pattern showed on a separate occassion multiple excited transverse modes. Shown in Fig. 13 are the beam frequency spectra[22] with and without transverse feedback at a beam current of 100 mA with $\nu_x = 0.618$ and $\nu_y = 0.637$. The frequency axis spanned 10 revolution harmonics. With feedback on, only the revolution harmonics were observed. With feedback off, multiple betatron tunes lines were present[23].

[17] log 19, pp. 116-119 (11/19/98), measurements by W. Barry, J. Fox, M. Minty, S. Prabhakar, D. Teytleman

[18] log 20, pp. 10-25 (11/21/98), measurements by M. Minty, U. Wienands

[19] log 20, pp. 10-25 (11/21/98), measurements by M. Minty, U. Wienands

[20] log 20, pp. 44-49 (11/22/98), measurements by S. Prabhakar, D. Teytleman, U. Wienands

[21] log 19, pp. 48-52 (11/14/98), measurements by Y. Cai

[22] log 20, pp. 76-87 (11/22/98), measurements by W. Barry, M. Minty

[23] note that the use of nonuniform fill patterns, in general, complicates the interpretation of the frequency spectrum

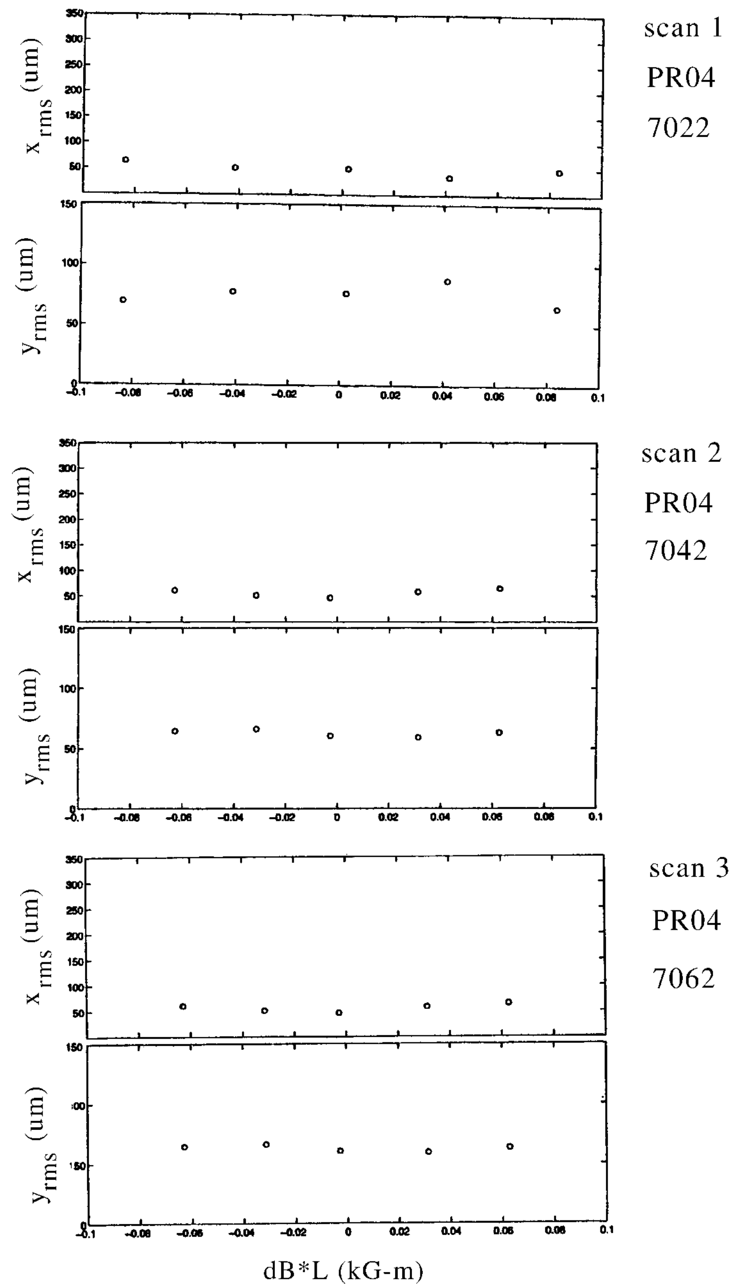

Figure 10: Measured BPM rms versus horizontal global orbit distortion with a 97-10 bunch fill pattern. Three correctors were used to fully span the HER 60° lattice. The full scale on the horizontal axis corresponds to ± 5 mm. The betatron tunes were $\nu_x = 0.6098$ and $\nu_y = 0.6283$. Transverse feedback was off.

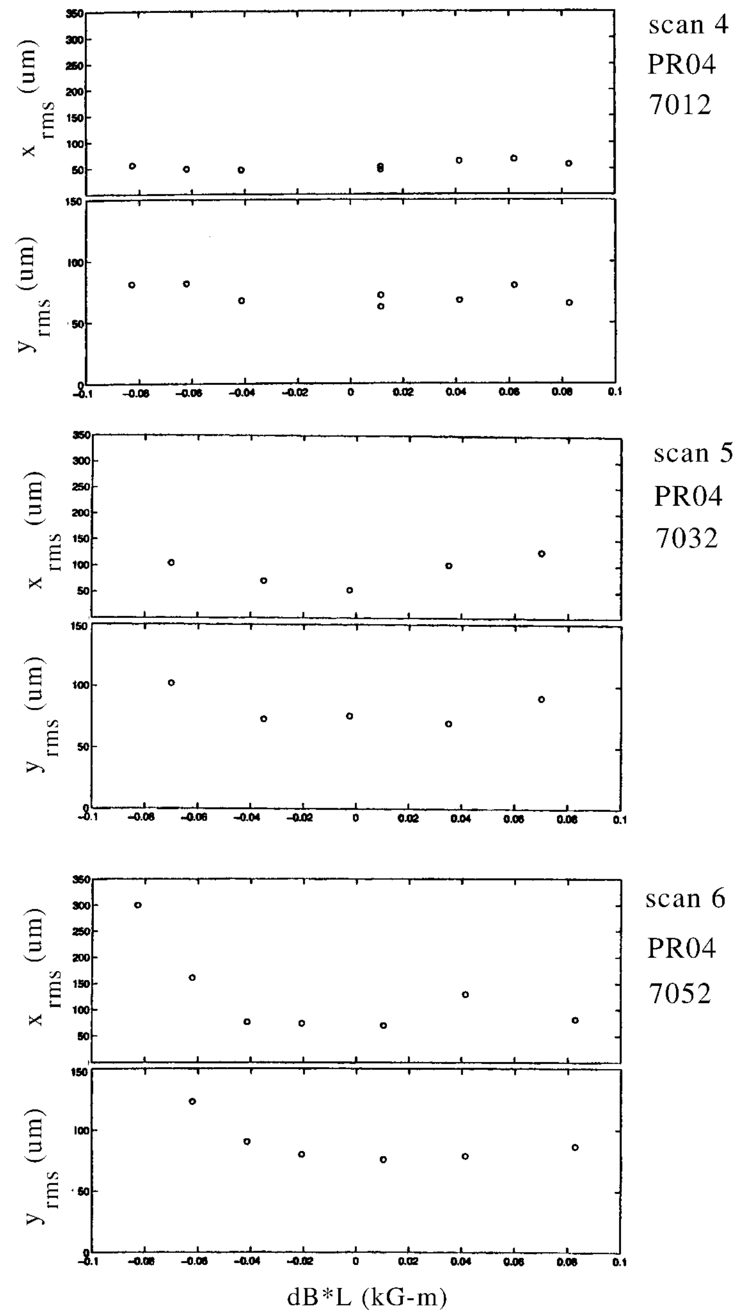

Figure 11: Measured BPM rms versus vertical global orbit distortion with a 97-10 bunch fill pattern. Three correctors were used to fully span the HER 60° lattice. The full scale on the horizontal axis corresponds to ±5 mm. The betatron tunes were $\nu_x = 0.6098$ and $\nu_y = 0.6283$. Transverse feedback was off.

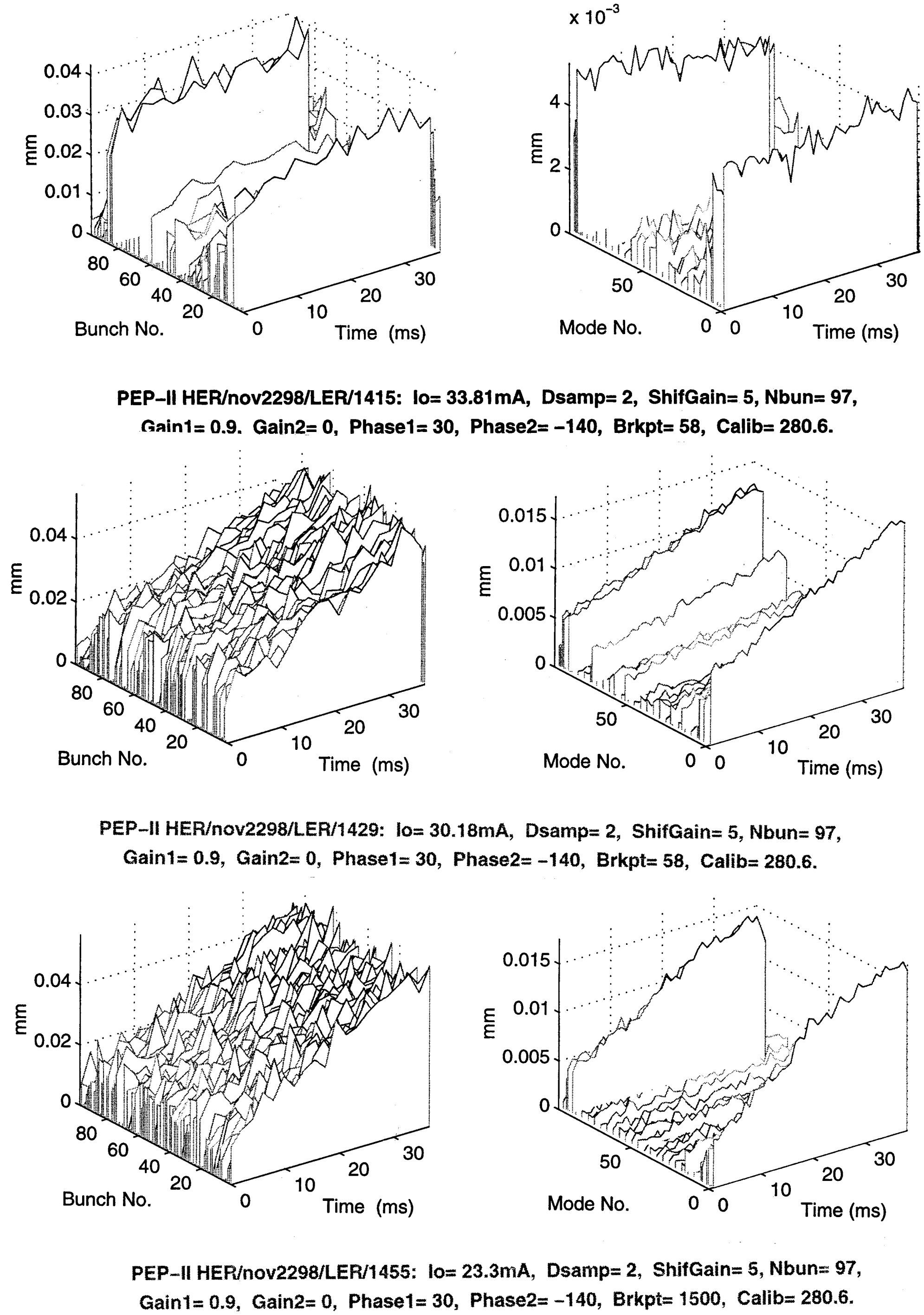

Figure 12: Growth rates with the 97-10 fill pattern versus vertical oscillation amplitude corresponding to nominal conditions (top), a -0.05 kG-m kick (middle), and a -0.075 kG-m kick (bottom) at PR04 YCOR 7052. Note the change in scale in the right-hand plots.

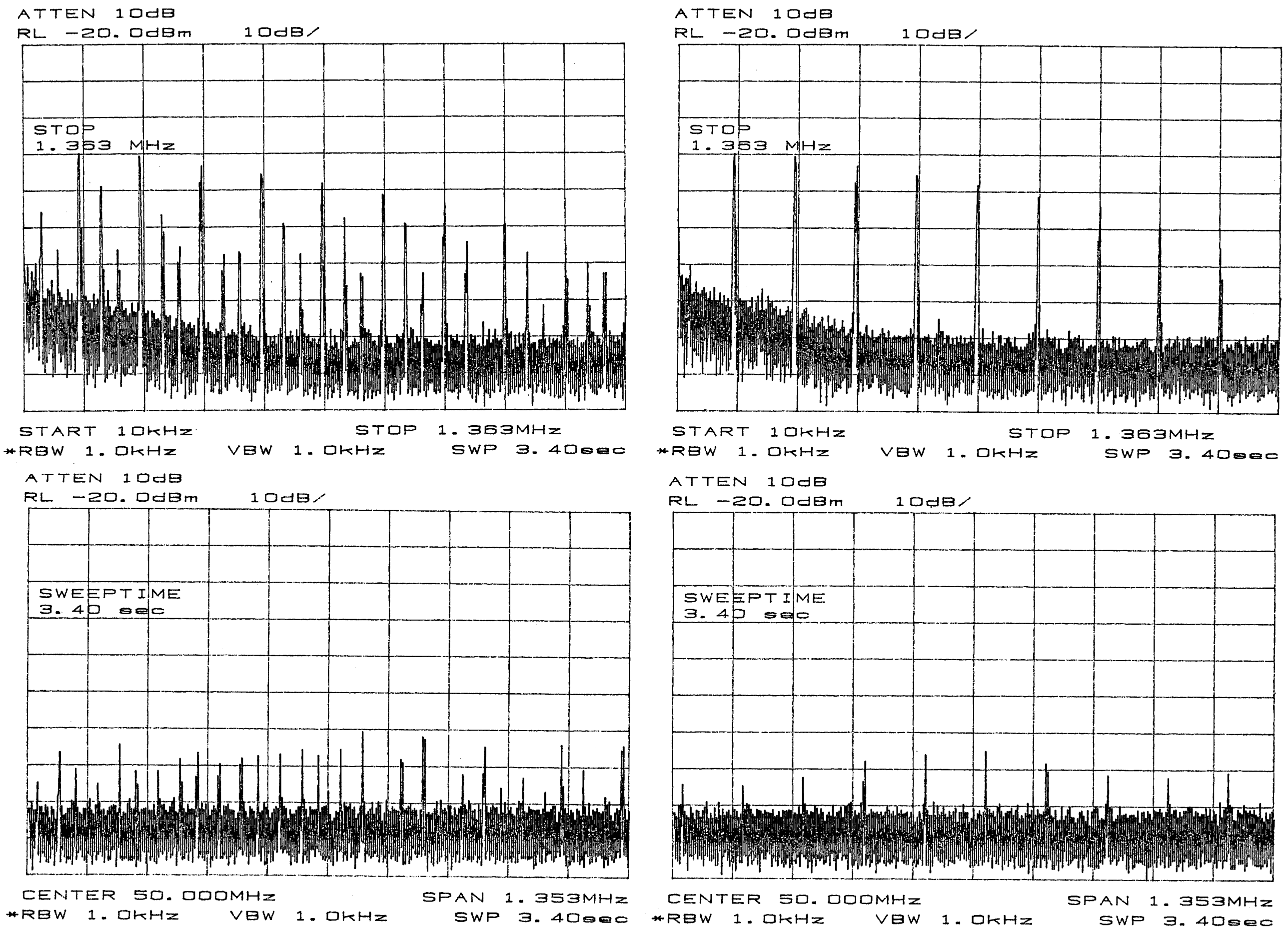

Figure 13: Horizontal (top) and vertical (bottom) frequency spectra with a 97-10 bunch fill pattern at 100 mA with transverse feedback off (left) and on (right).

Prior to experiments aimed at localizing a potential impedance source (followup to measurement of Figs. 10-12), the rms along the same 97-10 bunch pattern was measured to ensure data reproducibility. The first measurement[24] revealed a 20 μm rms in both x and y in two separate measurements with transverse feedback on. With feedback off, however, at 100 mA the average horizontal rms was about 500 μm while vertically about 80 μm was measured up through the last third of the fill pattern for which the rms increased towards 200 μm. In a second measurement[25] the beam centroid motion with transverse feedback off was recorded at up to 200 μm in both transverse planes. At the same time an orbit drift was documented showing rms variations in the beam orbit of up to 1.5 mm horizontally and 0.3 mm vertically within a 15 minute time period.

[24]log 20, p. 122 (11/25/98), measurements by T. Fieguth, Z. Kvitky, and M. Minty

[25]log 21,pp. 26-27 (11/27/98), measurements by M. Donald,Z. Kvitky, and M.Minty

The threshold measurement in the 97-10 fill pattern was later repeated as a reproducibility check prior to a study with varying cavity voltage. The repeated threshold measurement[26] is shown in Fig. 14. Comparison with Fig. 9 shows that the effect of the instability was somewhat reduced; the threshold measured at this time was about 60 mA in x and slightly higher, about 80 mA, in y.

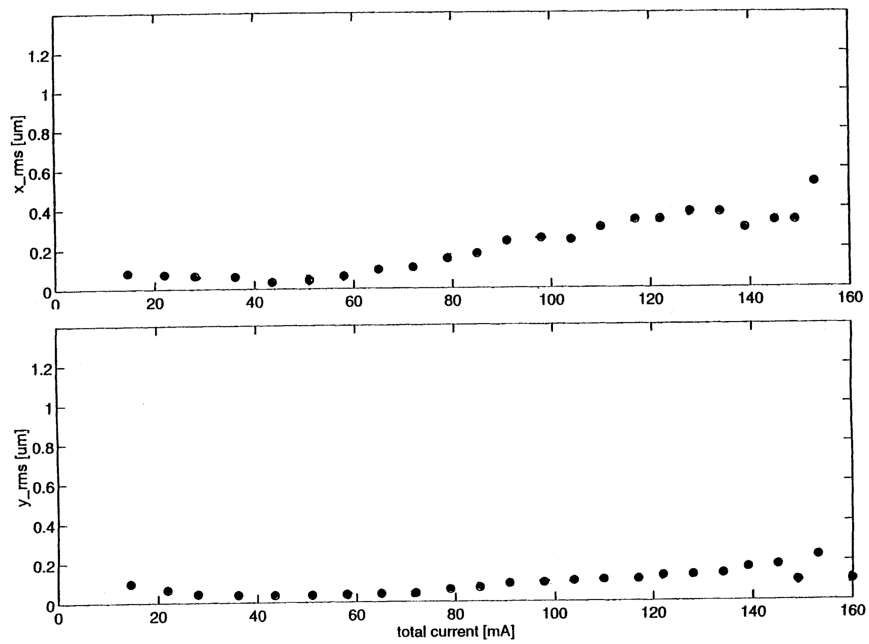

Figure 14: Second threshold measurement with a 97-10 bunch fill pattern with transverse feedback off. Compare with Fig. 9.

Another reproducibility check[27] measuring the rms along the fill pattern gave consistently over 3 successive measurements a position rms of 40 μm both horizontally and vertically at 50 mA which is consistent with the data of Figs. 10 and 11. The dependence of the position centroid rms on the bunch length was then measured[28] by varying the total cavity voltage (6.0, 7.2, and 8.4 MV) corresponding to about a 15% total change in bunch length. No differences were detected within the measurement resolution of about 5 μm.

Collimator heating studies[29] were undertaken by bypassing the water flow used for collimator cooling. With 150 and 200 mA in the 97-10 fill, both the collimator and bellows temperatures were observed to increase by about ten degrees Fahrenheit.

[26]log 20, pp. 158-159 (11/26/98), measurements by F.J. Decker, M. Minty

[27]log 20, p. 154 (11/26/98), measurements by M. Minty

[28]log 20, p. 155 (11/26/98), measurements by F.J. Decker, Z. Kvitky, and M. Minty

[29]log 21, pp. 40-43 (11/27/98), measurements by T. Mattison; log 21, pp. 156-159 (12/5/98), measurements by A. Kulikov

3.5 291 Bunch Even Fill Pattern

Early in the commissioning run, the bunch-by-bunch data acquisition system was used to measure vertical modes and growth rates with a 291 uniform bunch fill pattern. A single mode, mode-1, was observed[30] at 15 mA with a growth rate of 0.2 ms^{-1}. These data, shown in Fig. 15 were similar to observations from the July run [4].

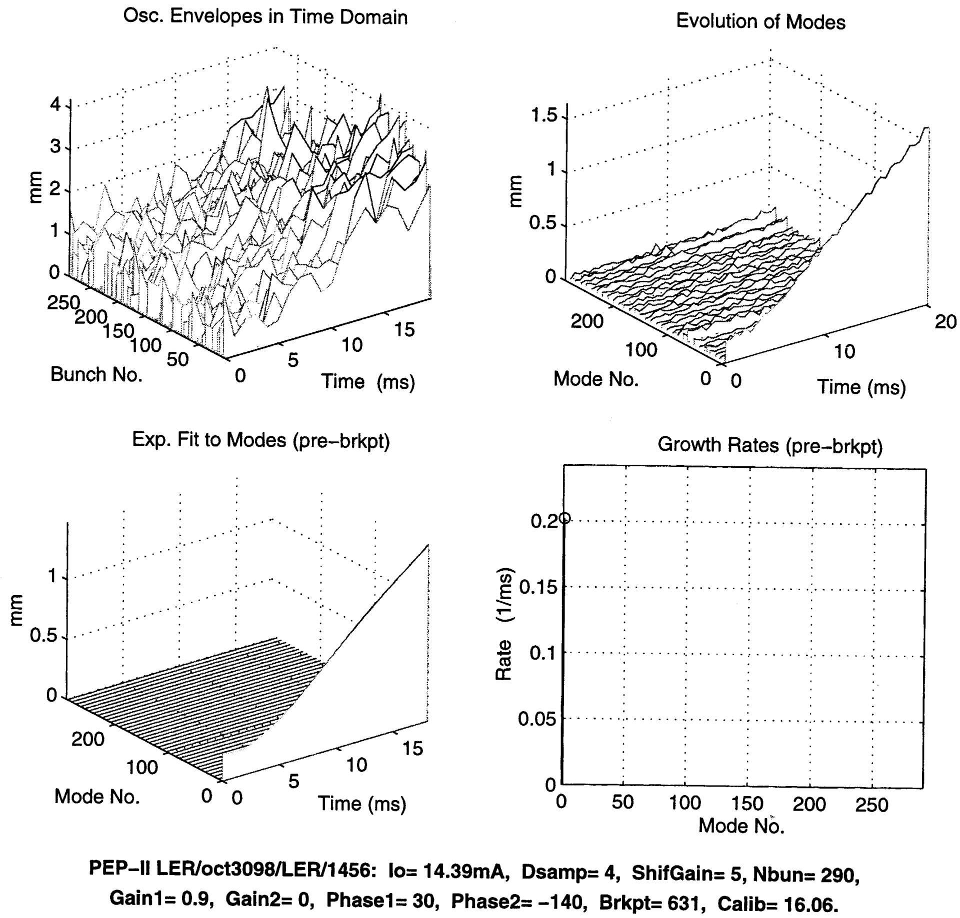

Figure 15: Modal analysis of 291 bunch uniform fill.

Collimator heating studies[31] were taken with a 291-30 fill. At 150 mA, both the collimator and bellows temperatures were observed to increase by a few degrees Fahrenheit. Comparison with data obtained with the 97-10 fill pattern revealed a dependence of the temperature rise on the beam frequency distribution.

After fine tuning the transverse feedback system at the higher current, the beam was observed to be stable[32] up to 270 mA in a fill pattern consisting of 291 bunches with a 30 bunch gap. This condition was used for subsequent collision studies.

[30] log 16, pp. 157-159 (10/30/98), measurements by W. Barry, J. Fox, S. Prabhakar, D. Teytelman

[31] log 21, pp. 156 and 159 (12/5/98), measurements by A. Kulikov

[32] log 21, pp. 1-13 (11/26/98) measurements by U. Wienands

3.6 Design Fill Pattern

Beam interactions causing beam loss motivated the use of non-interacting bunch fill patterns to allow for independent commissioning of the two accelerators. Comparatively little data were acquired with the design fill pattern as a consequence. With the design fill, consisting of 1648 bunches and an 87 bunch gap, the beam was injected using a '9-zone' filling sequence for which the beam was injected iteratively into 9 equidistant regions; that is, rather than injecting the beam sequentially, to avoid beam loss associated with bunch trains (see section 3.7), the beam was injected into a uniform fill mocking 9 macropulses. At that time up to 200 mA could be stored[33] with transverse feedback using a large bump near the injection septum.

The effect of the septum bump on the 1656 bunch beam (design fill including the 5% ion clearing gap) was measured using a closed vertical angle bump at the septum and measuring the BPM rms. The data[34] are shown in Fig. 16 at a 150 mA total beam current. The data seem to support the indication of a perturbation arising in the region of the septum. However, caution is needed in interpreting the data since the minimum rms observed clearly indicated that the beam was already significantly excited; the BPM rms measured were at 50 mA, 400μm and 210 μm and at 150 mA, 535 μm and 235 μm in x and y respectively.

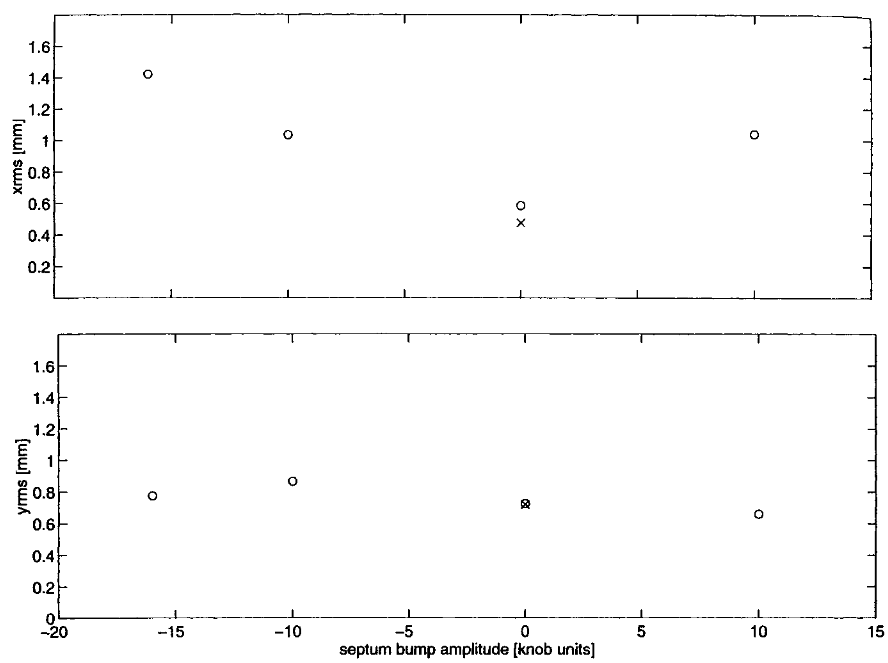

Figure 16: Measured BPM rms in x (top) and y (bottom) versus septum angle bump with the design (zone) fill pattern at 150 mA. The design $\beta-$functions at the selected BPM are $\beta_x = 17.5$ m and $\beta_y = 7.7$ m. The betatron tunes were unusually close ($\nu_x = 0.622$ and $\nu_y = 0.624$).

[33]log 19, pp. 48-52 (11/14/98) measurements by Y. Cai, U. Wienands

[34]log 19, pp. 71-72 (11/14/98), measurements by M. Minty

The Fourier spectra with the design fill pattern is given[35] in Fig. 17. The two predominant peaks are the horizontal betatron line and its alias. As documented previously with two bunches (see Fig. 2) evidence of both betatron coupling and synchro-betatron coupling was clearly observed. The mysterious peaks near the center of the frequency range correspond to $3 - 4\nu_x$ or 70.5 kHz and its alias at $4\nu_x - 2$ or 65.8 kHz. At this time, during commissioning of the bunch-by-bunch gating feature of the spectrum analyzer, there was simultaneously observed evidence[36] of longitudinal motion towards the back of the fill pattern. Longitudinal motion within the fill pattern had been observed in a previous commissioning period [8].

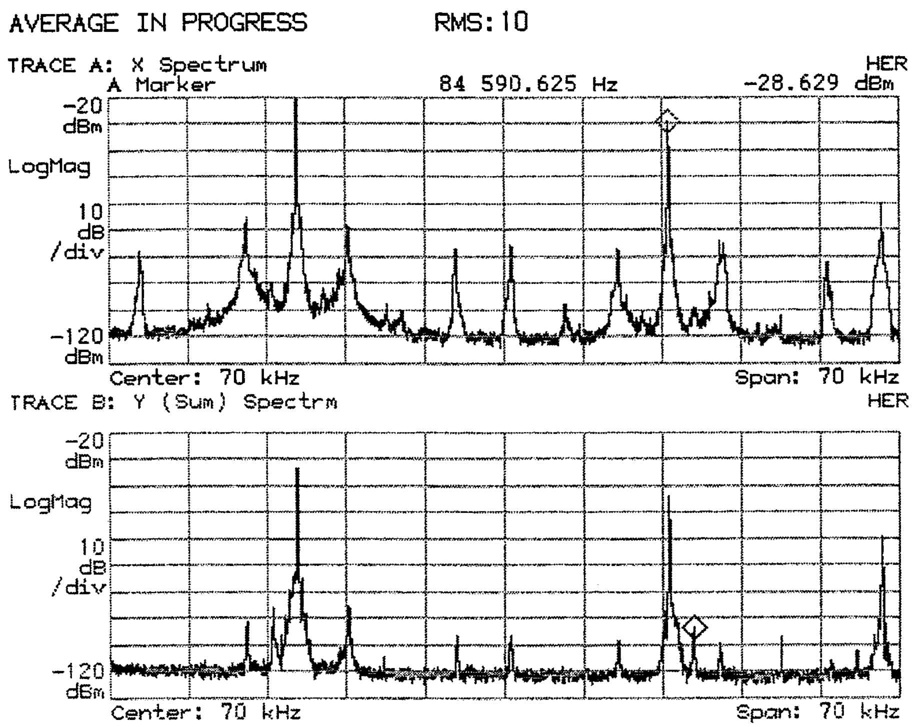

Figure 17: Betatron spectra with the design fill pattern at 150 mA measured with horizontal (top) and vertical (bottom) electrodes. The betatron tunes were $\nu_x = 0.6206, \nu_y = 0.6392$ and the synchrotron tune was, based on these data, $\nu_s \approx 0.033$.

3.7 Bunch Trains

Data taken with bunch trains revealed unexpectedly violent motion appearing first in the horizontal plane. The primary analysis tools for bunch train data included the spectrum analyzer, the beam current monitor, and the BPMs. The acquired data were not troubled by day-to-day reproducibility problems as had been occassionally observed with the more evenly spaced fill patterns.

[35] log 19, p. 84 (11/15/98), measurements by A. Fisher, M. Minty

[36] log 19, p. 78 (11/15/98) measurements by A. Fisher

The bunch train dynamics were first noted as an inability to inject sequential high current (about 1 mA compared to the design single-bunch beam current of 0.6 mA) bunches without transverse feedback. Shown in Fig. 18 are three measurements[37] showing the charge along the train for the indicated total number of bunches. The data were acquired by filling the train uniformly to 1 mA per bunch with transverse feedback on. The feedback loops were opened, first in y, and then in x. When the x loop was opened, substantial beam loss occured. The intensity profile was then measured as shown in the figure. The plots correspond to initial (final) beam currents after turning off transverse feedback of 30 mA/14.2 mA in 30 bunches (top plot), 40 mA/14.6 mA in 40 bunches (middle plot), and 50 mA/16.2 mA (bottom plot). Interestingly, it was noted that injecting sequentially with the transverse feedback loops off resulted in the same current distribution as shown in the Fig. 18; that is, the threshold for current loss was measured to be the same using two independent measurements. Note however, that the cited currents do not accurately represent the instability 'threshold', which is determined by the presence of *any* bunch motion as detected on the spectrum analyzer, for example.

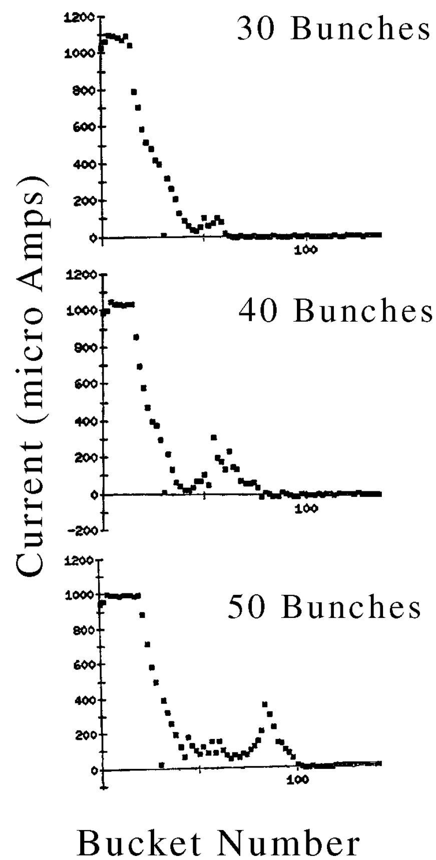

Figure 18: Measured current distribution along bunch trains of variable length after turning off the transverse feedback loops as measured by a beam current detector. The spacing between bunches was two buckets, or 4.2 ns.

[37] log 18, pp. 72-77 (11/8/98) measurements by M. Minty

Data taken with the same procedure using other train lengths gave initial (final) beam currents of 60 mA/20.5 mA in 60 bunches, 75 mA/20.5 mA in 70 bunches, 84 mA mA/21.3 mA in 80 bunches, and 94.6 mA/27.1 mA in 90 bunches. A summary[38] of the current threshold as determined by beam loss with variable length bunch trains is given in Fig. 19.

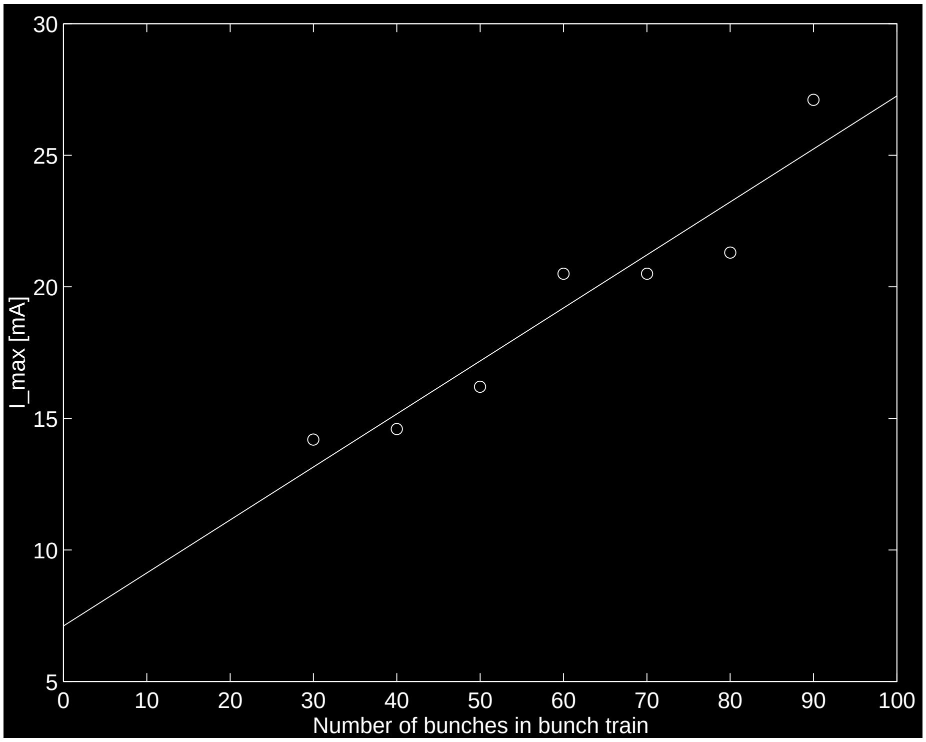

Figure 19: Measured threshold for current loss I_{max} in bunch trains with bunches spaced by two buckets.

To better understand the cause of beam loss, BPM data were acquired in the following way: 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 hand synchronized to acquire data while opening the horizontal feedback loop; that is, at the same time this loop was opened, the data records were acquired. To improve the probability of time-overlap between these events, the BPMs were sampled every 100th or 200th turn rather than turn-by-turn. These data[39] are shown in Fig. 20. The first column shows the measurements with the BPMs gated on bucket 60, or bunch 30. This corresponds to one of the low current pulses in Fig. 18 as evidenced by near zero current after the loop was opened. The second column shows measurements gated on bucket 30, or bunch 15, for which there was less current loss in the final state. Note that the finite bandwidth of the BPM electronics (around 20 MHz) causes dilution of the single-bunch measurement by inclusion of about ±10 buckets (or ±5 bunches in the every-other-bucket fill pattern) centered at the bunch of interest. Notice that the horizontal

[38]log 18, pp. 72-77 (11/8/98) measurements by M. Minty
[39]log 18, pp. 85-89, 91 (11/8/98) measurements by M. Minty

motion in this case has peaks at roughly the same time as the step decrease in beam current. This would suggest that saturation of the instability was not detected, rather, beam loss on physical or dynamic aperture occured. The peak-to-peak amplitude of horizontal motion was about ±5 mm at bunch 30 and about ±3 mm at bunch 15. The corresponding vertical motion, while significant particularly if normalized to the beam size, was considerably less.

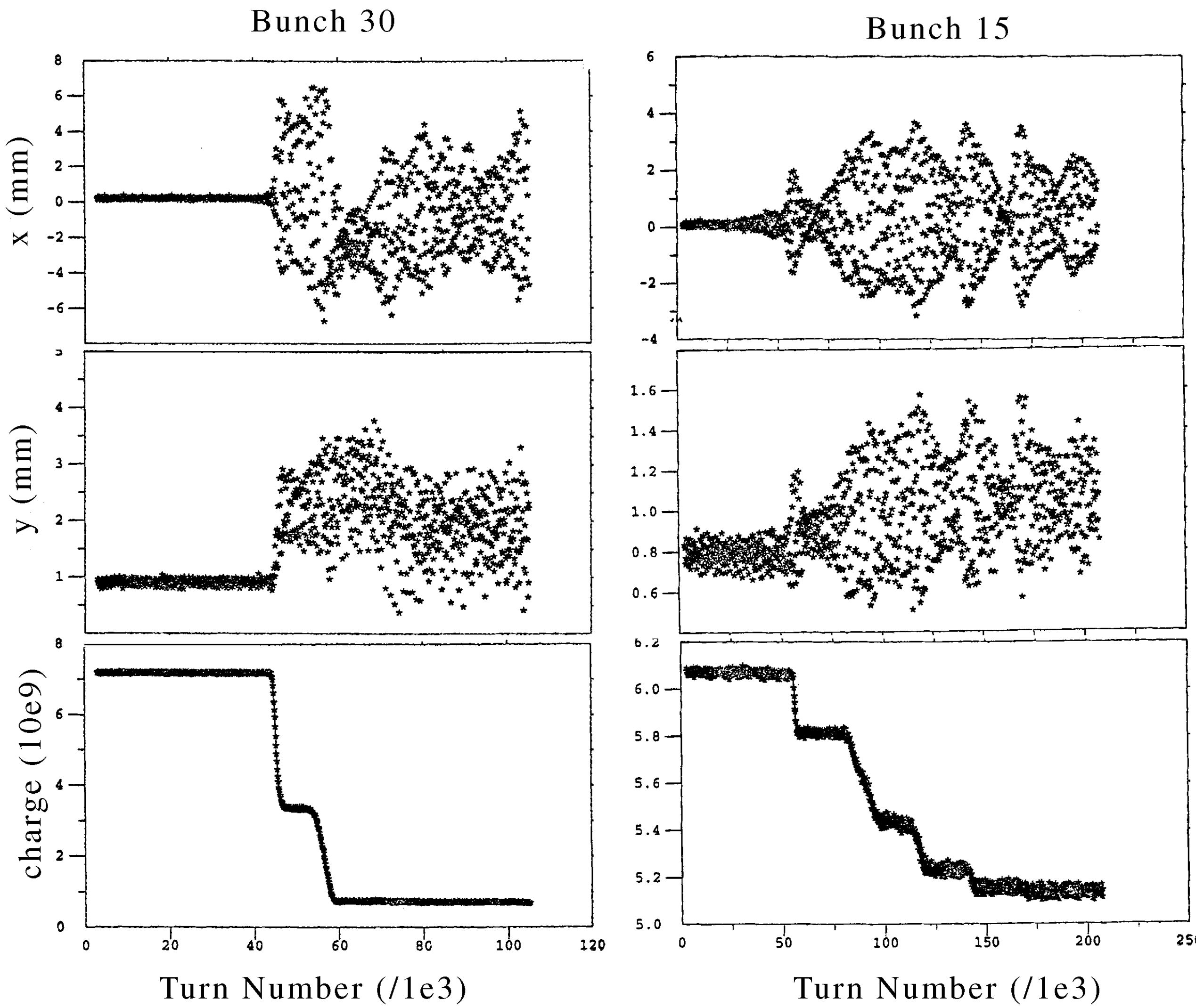

Figure 20: Transverse motion for selected bunches in a 50 bunch train recorded as transverse feedback was turned off. Plotted are the horizontal position (top), the vertical position (middle), and the beam intensity (bottom). Compare with Fig. 18.

With the 50 bunch train, experiments were carried out while varying the local vacuum pressure. In the first experiment, the pressure was increased by turning off pumps in two PR08 half arcs. The beam lifetime was observed to decrease from 1400 minutes to 400 minutes and the beam loss monitor signal amplitudes increased by a factor of 2-3 as a result of the pressure change. No change in the total storable current was observed[40] using the current monitor. In a later experiment, using the spectrum analyzer as a diagnostic, the measurement was repeated[41] with a 100 bunch train. The PR06 pumps and all the distributed ion pumps (except in arc 1) were turned off. At 10 mA, the beam lifetime was only 200 minutes. There was no significant change noted in the spectrum of the beam. These data suggest that ion effects are not a significant contribution to the observed coupled-bunch instabilities which is consistent with the observations of the July, 1998 commissioning run [4].

In a followup experiment the chromaticity, which affects the single bunch damping, was varied using the 50 bunch fill pattern. Shown in Fig. 21 is the measured[42] current profile taken with transverse feedback off at two different values of chromaticity. In the top plot the maximum attainable current was about 15 mA while with higher chromaticity up to 80 mA was stored.

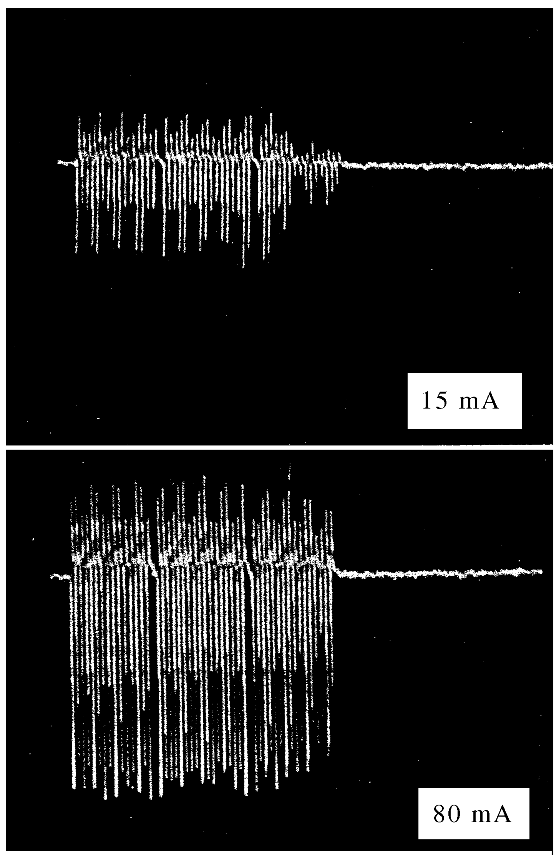

Figure 21: Bunch intensity along a 50 bunch train at relative-to-nominal chromaticity changes of [+4,+2] (top) and [+5,+5] (bottom) in x and y respectively. With high chromaticity significantly more charge was stored.

[40] log 18, p. 94 (11/8/98) measurements by A. Kulikov
[41] log 22, p. 7 (12/6/98) measurements by A. Kulikov
[42] log 19, pp. 31-38 (11/14/98) measurements by J. Clendenin

The time-sequenced data are show in Table 2 which gives the maximum storable beam current without loss I_{max} versus change in horizontal $\Delta\xi_x$ and vertical $\Delta\xi_y$ chromaticity. Apparently, during the measurements conditions changed since the last two data points at high chromaticity have a relatively low total current threshold. Unfortunately, the frequency spectrum of the beam was not recorded at high chromaticity.

$\Delta\xi_x$	$\Delta\xi_y$	I_{max} (mA)
+2	+2	13
-1	-1	13
+6	+6	> 80
+4	+4	> 80
+2	+3	18
+1	+4	20
+5	+5	> 80
+4	+5	20
+5	+4	18

Table 2: Measured threshold for current loss I_{max} versus relative change in chromaticity ($\Delta\xi_x$ and $\Delta\xi_y$) with a 50 bunch train.

The sensitivity of the threshold to betatron tunes was also checked first over a range of about 0.1 units. Shown in Fig. 22 are spectra measured[43] at different betatron tunes. The threshold at which the betatron lines appeared was below 10 mA in all cases which suggests that this instability was insensitive to tune changes at the level of ± 0.05.

By gating the spectrum analyzer, the betatron spectra for different bunches along a 45 bunch train of about 10 mA are shown in Fig. 23 during a study pertaining to the beam size. These data[44] show considerably less motion in the fully coupled, or round-beam case, as compared to the uncoupled, flat-beam case. The tunes in these data were not documented.

Spectrum analyzer data of a 20 bunch train were also taken and later analyzed offline. The measurements[45] are shown in Fig. 24 which shows the ungated spectrum of the bunches in both planes with feedback off versus total current. The two peaks near 70 kHz were of some concern since they were the only unidentified peaks in the spectrum. With betatron tunes of $\nu_x = 0.6223$ and $\nu_y = 0.6398$, the nearest possible candidate for a resonance was $4\nu_x - 2$ and $3 - \nu_x$. While these peaks did not appear in the 50 bunch train spectra, they were observed with the design fill pattern[46] and deserve further investigation.

[43]log 19, pp. 39-41 (11/14/98) measurements by J. Clendenin

[44]log 18, pp. 108-113 (11/14/98) measurements by A. Kulikov, U. Wienands

[45]log 18, p. 72 (11/8/98) measurements by M. Minty

[46]see Fig. 17 from log 19, p. 84 (11/15/98) measurements by A. Fisher and log 19, p. 86 (11/15/98) measurements by persons unknown

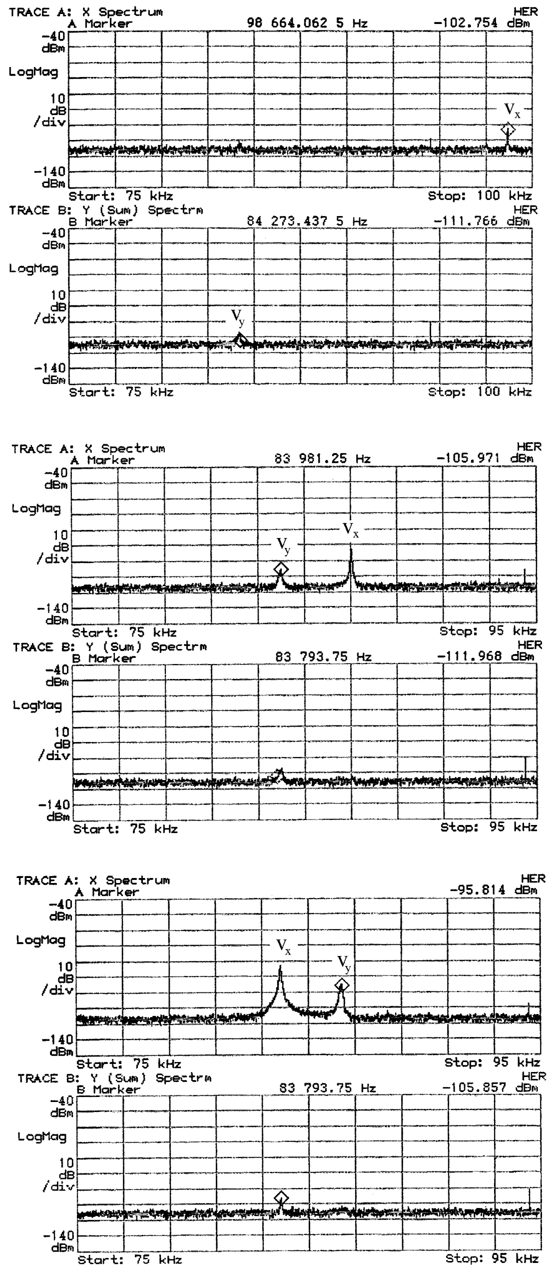

Figure 22: Spectrum analyzer data taken with a 50 bunch train at horizontal (ν_x) and vertical (ν_y) betatron tunes of 0.724/0.617 (top), 0.638/0.616 (middle), and 0.619/0.718 (bottom). The total current was less than 10 mA in these measurements.

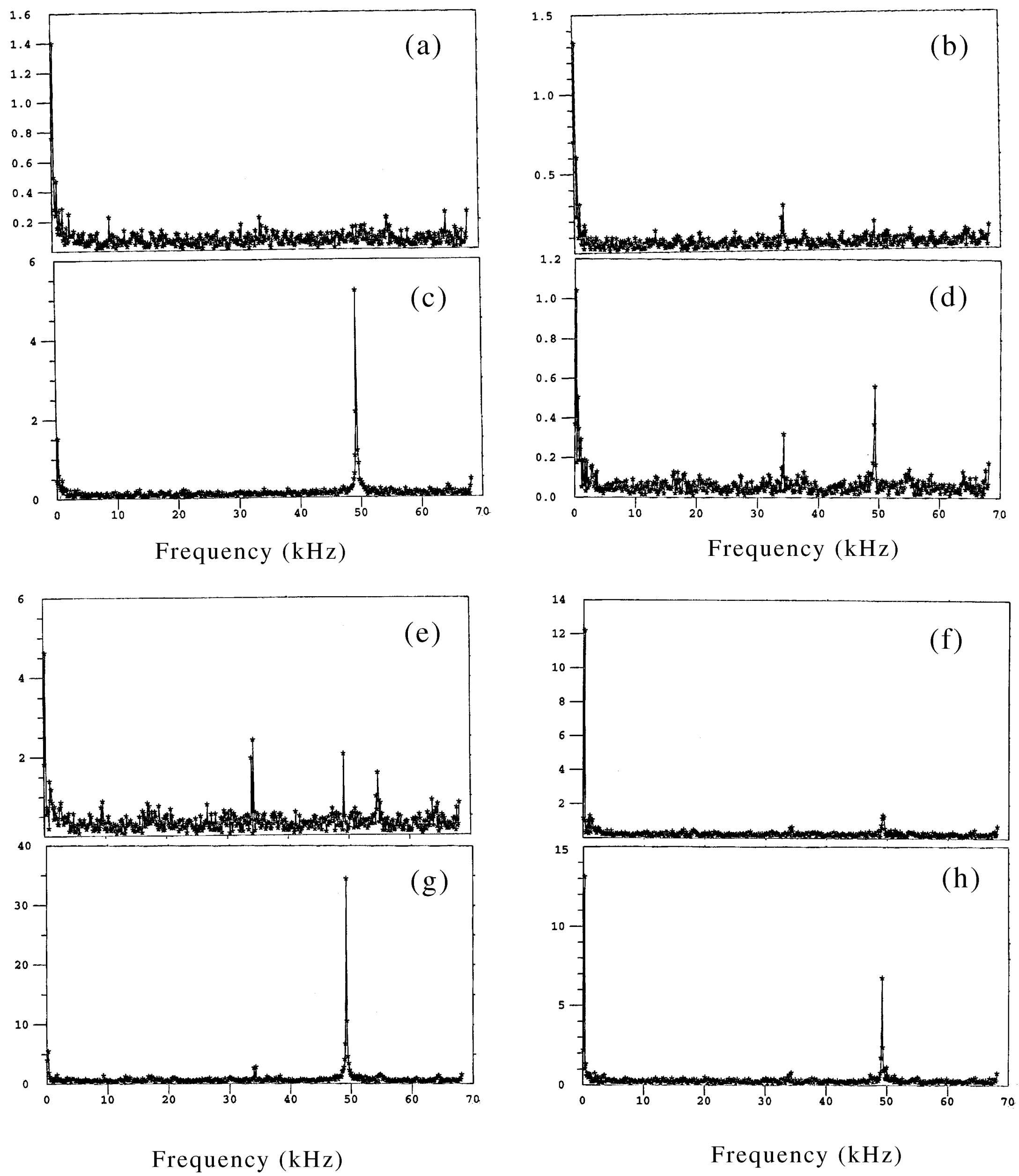

Figure 23: Spectrum analyzer data taken with a 45 bunch train on (a,b and e,f) and off (c,d and g,h) the coupling resonance. The top four plots were taken with the spectrum analyzer gated on bunch 35 while the bottom 4 plots are for bunch 50. The total current was less than 10 mA in both cases.

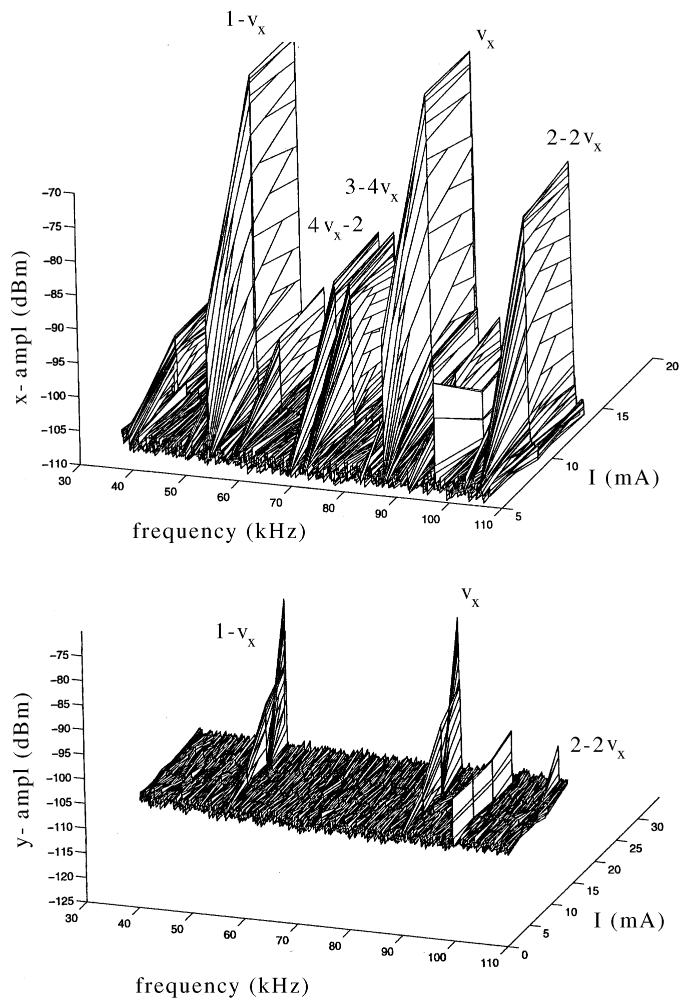

Figure 24: Spectrum analyzer data taken with a 20 bunch train at various beam currents with $\nu_x = 0.6223$ and $\nu_y = 0.6398$. The mysterious peaks at $3 - 4\nu_x$ and $4\nu_x - 2$ were also observed (see Fig. 17) with the design fill pattern. The line near 94.5 kHz is instrumental.

The effect of the cavity tuner positions was studied[47] using a 50 bunch train with a current loss threshold of 11.2 mA. In this study the tuners for the two parked cavities (8-3 and 8-5) were moved from their parked positions corresponding to 340 kHz to either 476 kHz or 204 kHz. No change in threshold for current loss was detected.

The reproducibility of the bunch train data was demonstrated[48] as shown in Fig. 25. Shown are photographs of the bunch intensity monitor with transverse feedback on (left) and off (right) with an initial fill of 30 mA. As observed previously, opening the vertical loop had no effect on the beam motion, but opening the horizontal loop caused significant beam loss (compare with Fig. 18).

[47] log 19, p. 24 (11/18/98) measurements by M. Ross
[48] log 21, p. 145 (12/4/98) measurements by M. Minty

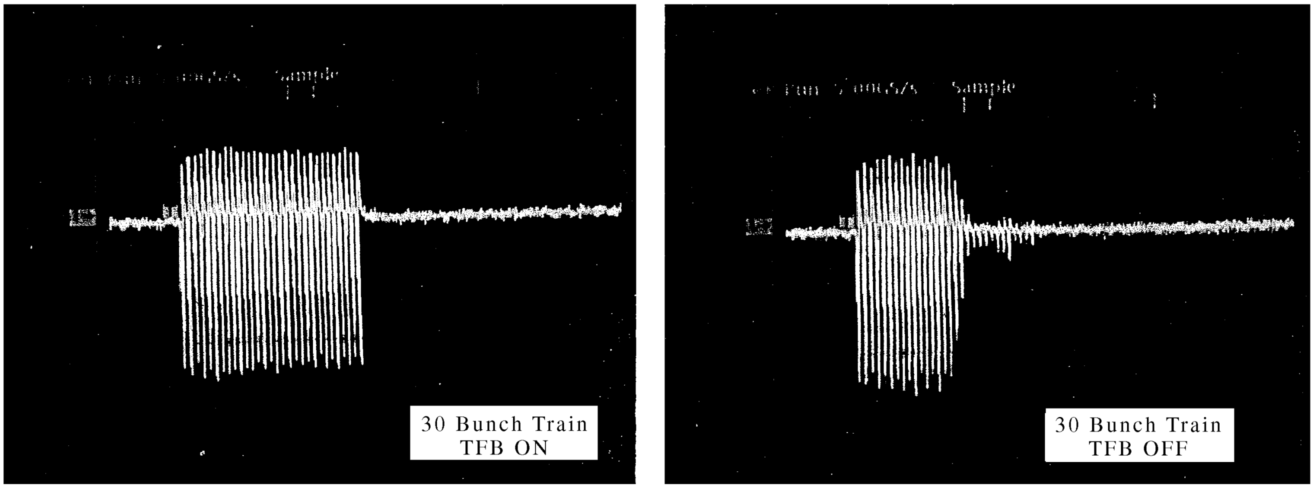

Figure 25: Bunch intensity monitor data with a 50 bunch train spaced by 2 buckets with and without transverse feedback. Compare with Fig. 18.

In previous studies[49] it had been noted that increasing bunch spacing significantly increased the total current one could inject with feedback off. In a follow up experiment[50], the beam current along the train was measured at different beam currents as shown in Fig. 26. As the charge per bunch was increased, beam loss occured starting at the tail of the train and moved forwards within the train as the current was increased. From these data, the threshold for current loss was between 16.5 mA and 18 mA with a 2 bucket spacing.

In spectrum analyzer data taken concurrently[51], from frequency distributions measured using a spectrum analyzer, the threshold for excitation at the betatron peaks was observed to be between 10.5 mA and 16.5 mA; the last two observations showed that the beam was excited transversely at detectable levels even though no beam loss occured; i.e. the beam motion was significant prior to beam loss.

Similar data were taken with the 100 bunch train and a bunch spacing of 4 buckets. These data[52] are shown in Fig. 27. These data are qualitatively similar to Fig. 26 however the threshold for beam loss was observed to increase significantly to about 30 mA. Data taken concurrently with the spectrum analyzer showed self-excited betatron tune lines[53] occuring between 17.9 mA and 26.9 mA.

With a 100 bunch train with spacing of 2 buckets, the transverse position rms along the train was measured[54] for different beam currents as shown in Fig. 28. These data show clearly the self-excitation of the beam moving towards the front of the train as the beam current was increased. These data support previous results (see Figs. 20 and 24) that the excitations were preceeded by motion in the horizontal, as opposed to vertical, plane.

[49]log 18, pp. 94-95 (11/8/98) measurements by A. Kulikov
[50]log 21, p. 150 (12/4/98) measurements by M. Minty
[51]see for example, log 21, p. 151 (12/4/98) measurements by M. Minty
[52]log 21, p. 153 (12/4/98) measurements by M. Minty
[53]see for example, log 21, p. 154 (12/4/98) measurements by M. Minty
[54]log 21, pp. 149 and 152 (12/4/98) measurements by M. Minty

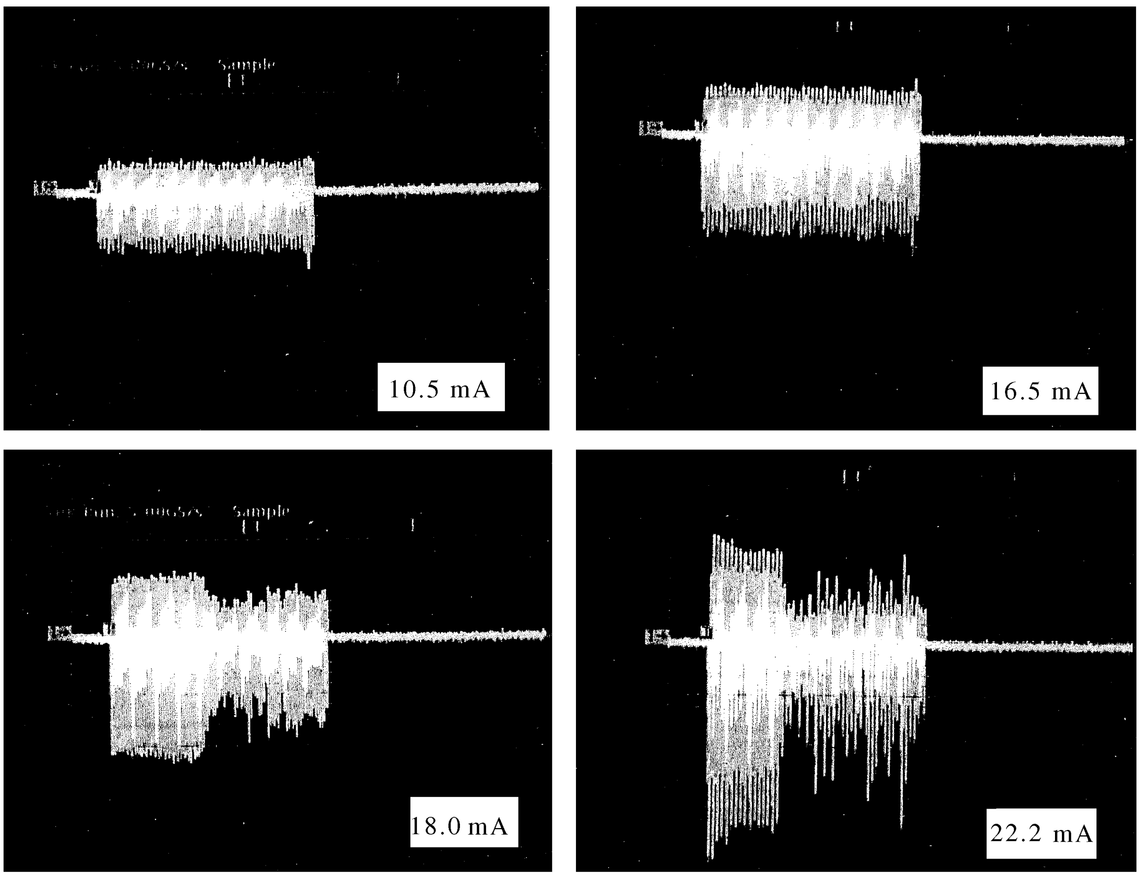

Figure 26: Bunch intensity monitor data with a 100 bunch train spaced by 2 buckets with transverse feedback off at different beam current.

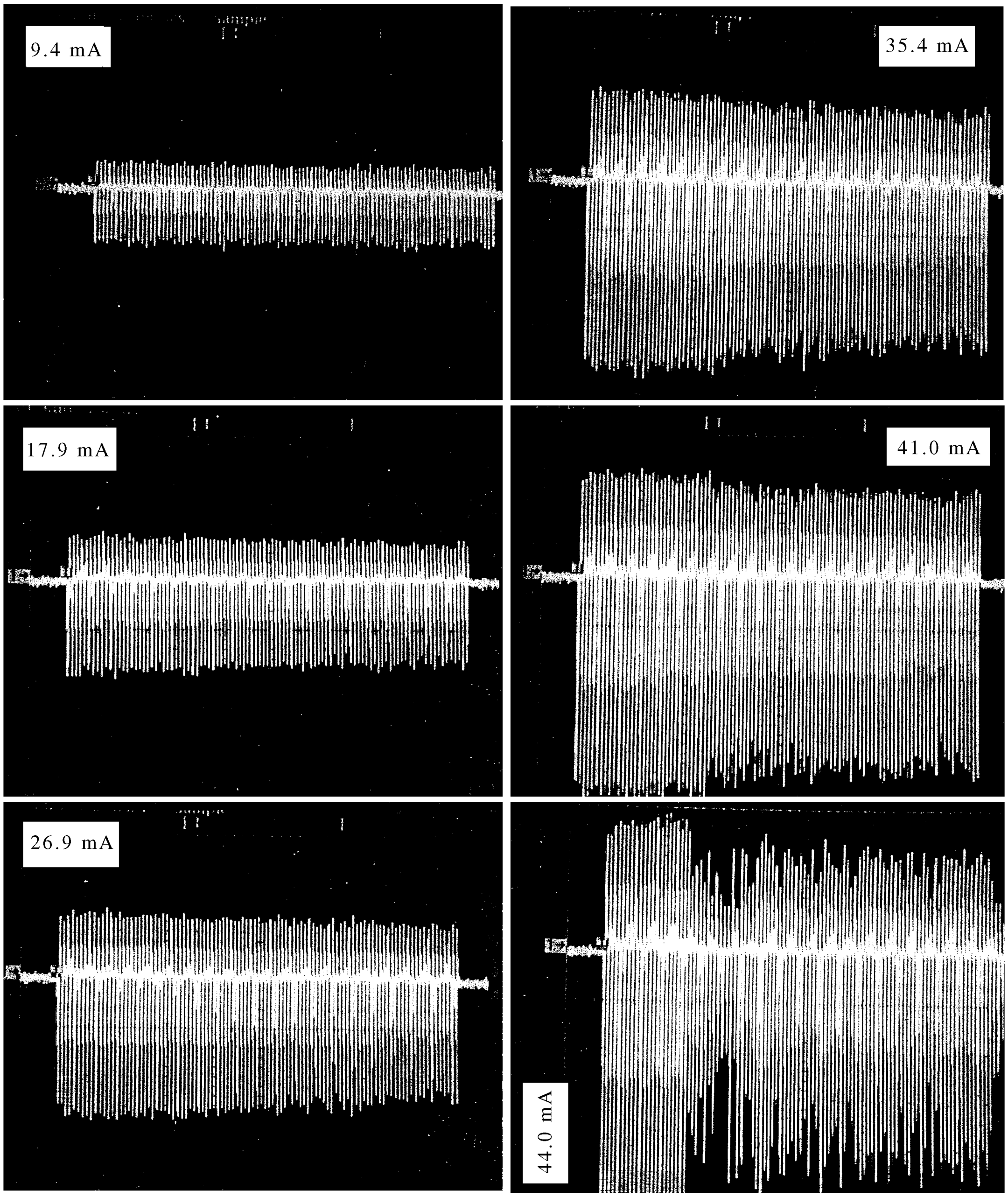

Figure 27: Bunch intensity monitor data with a 100 bunch train spaced by 4 buckets with transverse feedback off at different beam currents.

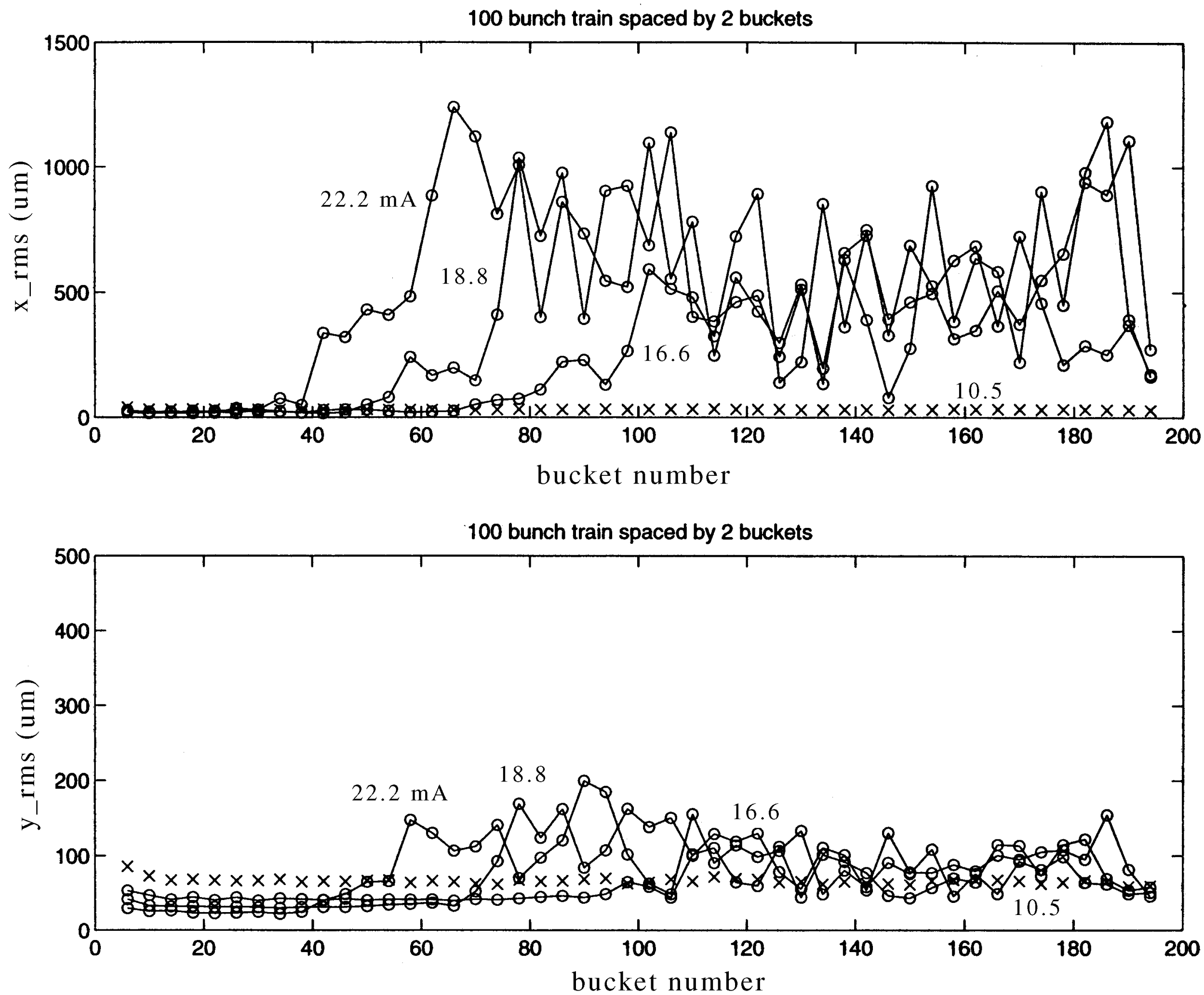

Figure 28: Growth in distribution of bunch centroid along a 100 bunch train with bunches spaced by two buckets for different beam currents.

Measurements were also taken with a 100 bunch train of 4 bucket spacing[55] for different beam currents. These data are shown in Fig. 29. Comparison with Fig. 28 shows that for a fixed current, roughly a factor of two in distance along the train was gained before the onset of the transverse motion.

[55]log 21, pp. 149 and 152 (12/4/98) measurements by M. Minty

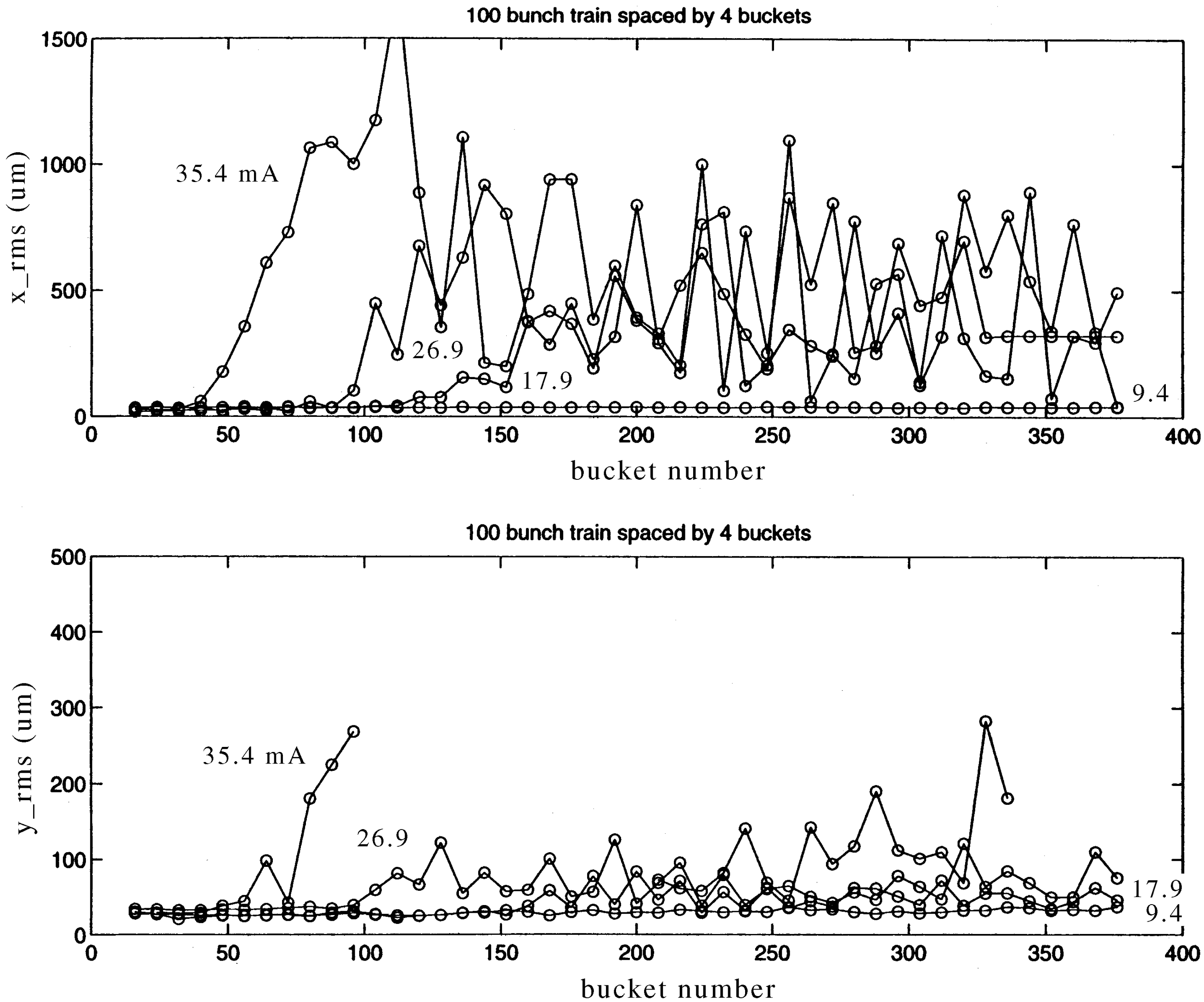

Figure 29: Growth in distribution of bunch centroid along a 100 bunch train with bunches spaced by 4 buckets for different beam currents. In the 35.4 mA total current case, some of the data were lost.

By observing the onset of self-excited betatron tune lines, the instability threshold was measured[56] as a function of bunch spacing. These data are shown in Fig. 30 for a 100 bunch train. The data are, curiously, well fit with a cubic fit and agree well with the two previous measurements which are not plotted.

[56]log 22, p. 15 (12/6/98) measurements by A. Kulikov

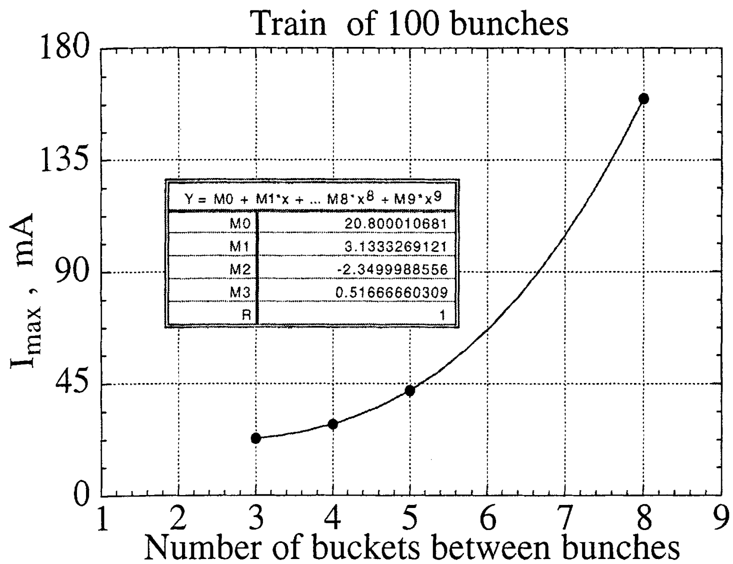

Figure 30: Instability threshold measured versus bunch spacing along a 100 bunch train.

3.8 Other Measurements

Data were acquired[57] using a clearing electrode as a pickup for detecting the presence of ions. These data are shown in Fig. 31 which shows the detected current in the interaction region versus applied voltage for different, equally-spaced bunch fill patterns and total beam current.

The dependence of the transverse tunes on beam current was measured. Shown in Fig. 32 are two sets of data taken with a single[58] bunch (left) and a set with 291-30 bunches[59] (right). The data are summarized in Table 3. Interestingly, the multiple bunch measurement differs significantly from a previous measurement[60]. With 291 equally spaced bunches, the tune shifts measured then, over the range of 0-55 mA total beam current (or ≈200 μA per bunch) were $\frac{\delta\nu_x}{dI} = +2.05 \times 10^{-5}$ mA^{-1} and $\frac{\delta\nu_y}{dI} = -2.56 \times 10^{-5}$ mA^{-1}.

N_b	$\frac{d\nu_x}{dI}$ (mA^{-1})	$\frac{d\nu_y}{dI}$ (mA^{-1})
1	$-(38.1 \pm 2.7) \times 10^{-5}$	$-(108.5 \pm 7.7) \times 10^{-5}$
1	$-(22.8 \pm 1.5) \times 10^{-5}$	$-(56.4 \pm 2.8) \times 10^{-5}$
291-30	$-(78.9 \pm 50.3) \times 10^{-5}$	$-(821 \pm 47) \times 10^{-5}$

Table 3: Measurements of horizontal ($\frac{d\nu_x}{dI}$) and vertical ($\frac{d\nu_y}{dI}$) tune shift with current. The number of stored bunches was N_b. The spectrum analyzer was not gated.

[57] log 17, p. 132 (11/3/98) measurements by S. Ecklund, A. Kulikov, C. Steier (visitor from Bonn), and U. Wienands

[58] log 19, pp. 11-13 (11/13/98) measurements by Y. Cai

[59] log 21, pp. 37-38 (11/27/98) measurements by T. Mattison

[60] the data from 1/18/98 may be viewed in reference [1]

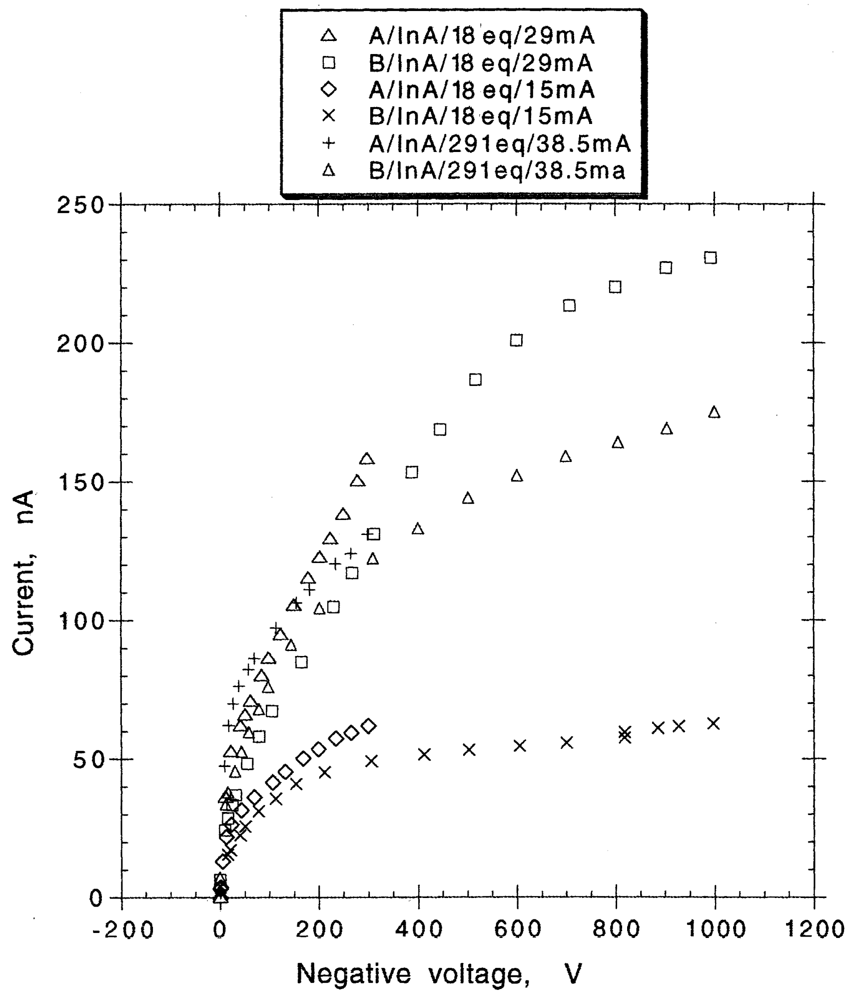

Figure 31: Detected current on a clearing electrode as a function of applied voltage for different evenly spaced bunch fill patterns.

A series of measurements were made[61] towards the end of the commissioning period using different numbers of evenly spaced bunches and either equal or unequal current populations while maintaining a constant average current per bunch (equal to the design single-bunch beam current of 0.6 mA). In the nominal case, bunches were populated equally. In the other case, every even bunch had 0.9 mA while every odd bunch had 0.3 mA. The BPMs were used as a diagnostic. The measured rms (determined offline with cuts on electronic systematics and 'flier' pulses) of the horizontal motion are shown in Fig. 33. The vertical beam motion (not shown) was relatively uninteresting since the amplitude was small and the scatter in the data taken at higher beam currents was large.

[61]log 22, pp. 123-133 (12/13/98) measurements by M. Stanek and T. Smith

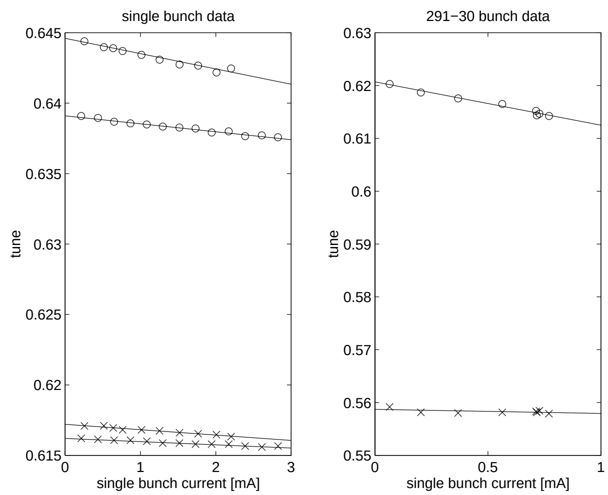

Figure 32: Tune shift with current measured with a single bunch (left) and with 291-30 bunches (right) showing measured horizontal tune (crosses) and vertical tune ν_y (circles). The slopes, given in Table 3, differ significantly from previous data [1] from January, 1998.

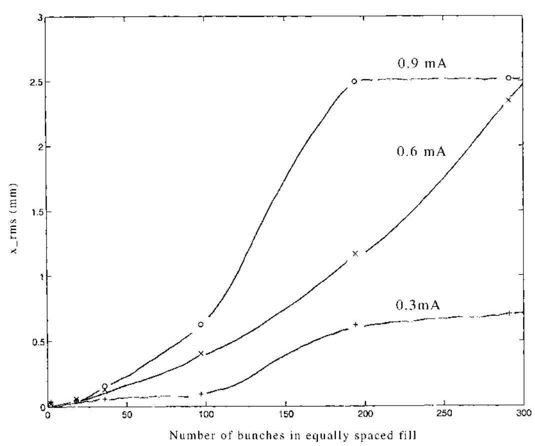

Figure 33: Horizontal beam centroid rms as a function of the number of bunches in uniformly spaced fill patterns with transverse feedback off. Two sets of data are shown: the middle curve corresponds to 0.6 mA per bunch; the top curve has even bunches with 0.9 mA and the bottom curve has odd bunches with 0.3 mA.

4 Low Energy Ring Measurements

In general, equally spaced bunches in LER behaved considerably more stably transversely as compared with the HER beam. Longitudinally, however, the beam was considerably more unstable. Bunch trains were also found to exhibit peculiar behaviour which for obvious reasons can not, as in the case of the electron beam, be attributed to ion effects. However electron cloud instabilities can not be excluded.

4.1 97 Bunch Even Fill Pattern

With a uniform bunch fill pattern, the measured[62] position rms (after offline processing) is shown in Fig. 34. While the absolute level was subsequently shown to depend on the BPM calibration, this level was unchanged both with and without transverse feedback indicating that the beam was stable up to the maximum sampled current of 50 mA.

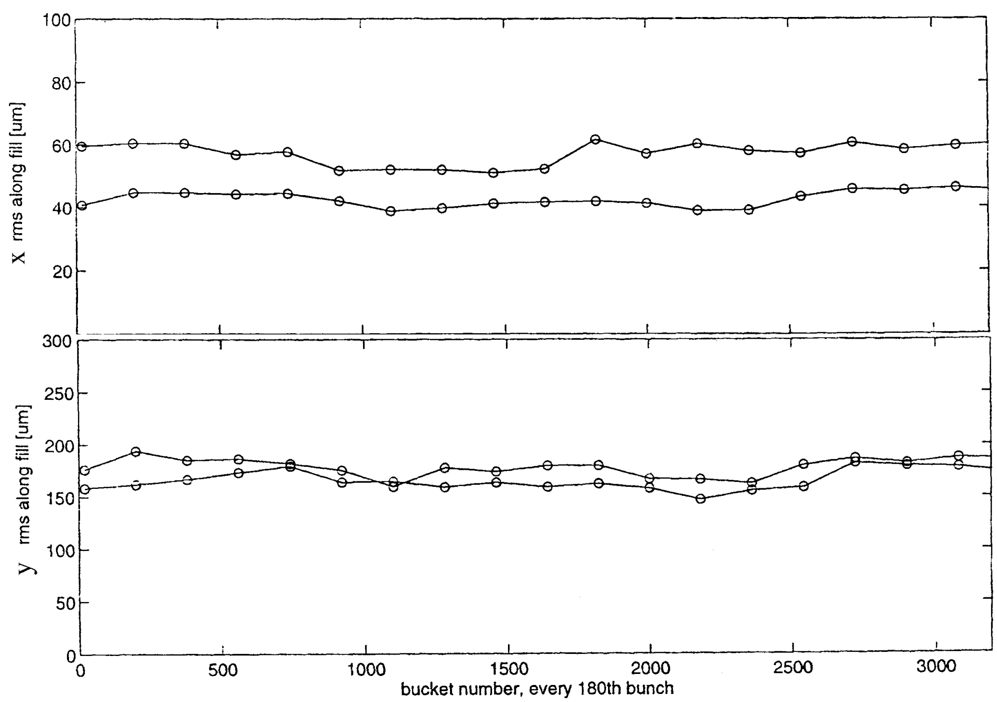

Figure 34: Offline filtered beam position monitor (BPM) data showing the rms of the BPM measurements for a 97 bunch uniform fill pattern in the horizontal (top) and vertical (bottom) planes with transverse feedback off. Every 180th bunch was sampled in these data. The two curves (connecting the points to guide the eye) correspond to two separate measurements.

[62]log 8, p. 61 (11/28/98), measurements by M. Minty, and J. Seeman

The Fourier spectrum as obtained from BPM measurements was measured[63] as a function of total current with 97 evenly spaced bunches and transverse feedback off. The data are shown in Fig. 35. Up to 100 mA the spectrum was relatively quiet, however at higher currents, longitudinal motion at $f_s \approx 4.7$ kHz clearly dominated the spectrum.

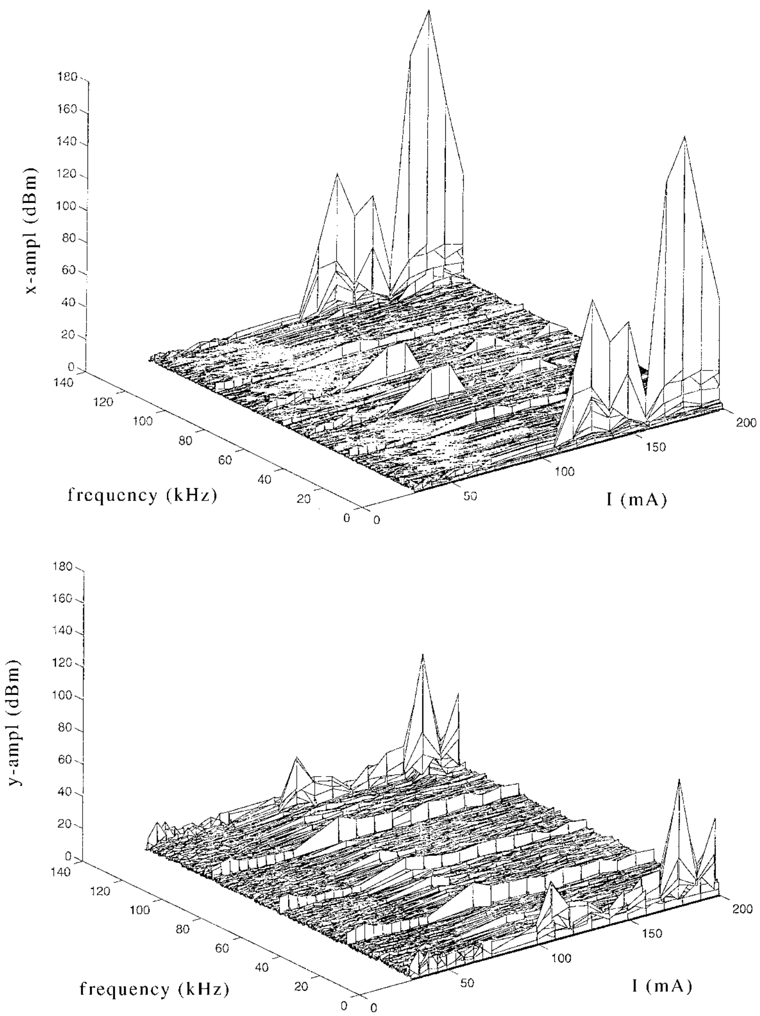

Figure 35: Fourier spectra obtained from horizontal (top) and vertical (bottom) BPMs gated on a single bunch in a 97 bunch uniform fill as a function of total current in both x (top) and y (bottom). Both longitudinal and transverse feedback were off.

[63]log 8, p 61 (11/28/98) measurements by M. Minty, J. Seeman

4.2 291 Bunch Even Fill Pattern

Fourier spectra derived from beam position monitor measurements were also acquired[64] in this fill pattern as shown in Fig. 36 at a total current of 200 mA. The measurements revealed significant longitudinal oscillations (the scale is 200 μm per 100 counts corresponding to 9° of phase excursion at 160 counts assuming the design dispersion at the selected BPM) and very little transverse motion. The rms motion along the fill is shown in Fig. 37 after a cut on longitudinal motion at the synchrotron frequency has been made. This demonstrates clearly that the rms of the beam centroid motion was dominated by dynamics in the longitudinal plane.

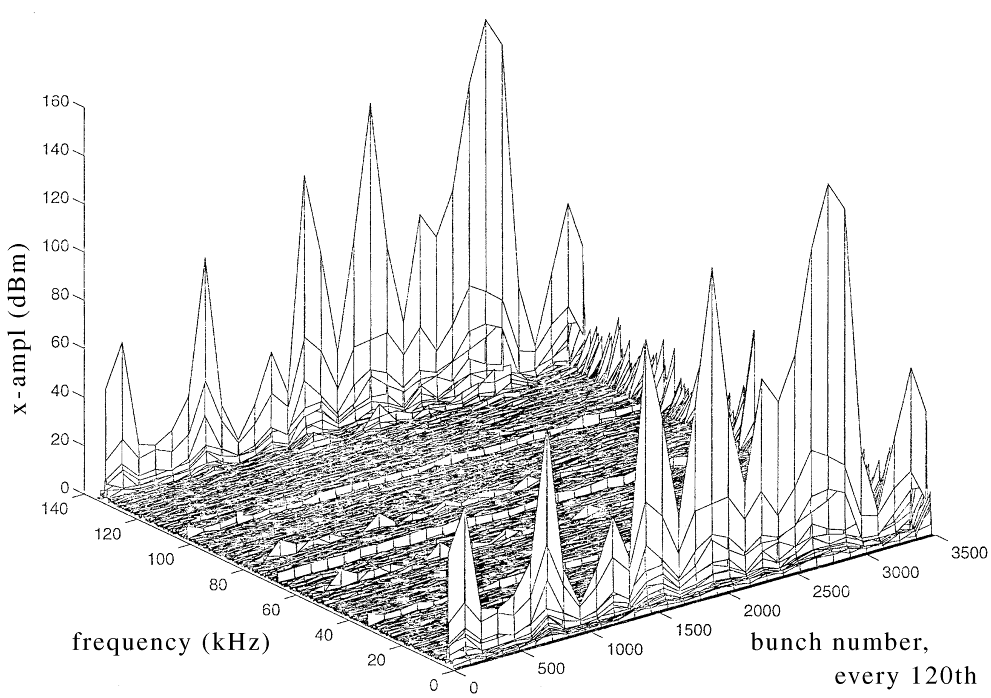

Figure 36: Horizontal Fourier spectra obtained using BPMs sampling a single bunch in a 291 bunch uniform fill as a function of distance along the fill pattern. The total beam current ws 200 mA.

In this fill pattern, the vertical frequency spectrum over the range of 290 to 308 times the revolution frequency and encompassing the betatron frequency at 39.6 MHz was measured[65] at 80 mA. The data are shown in Fig. 38 with (top) and without (bottom) transverse feedback. The peaks correspond to revolution harmonics. Data acquired[66] at 80 mA over the range of 1-1.5 times the betatron frequency also revealed about a small 2 dB excitation above the noise floor centered around 52 MHz.

[64]log 8, p 73 (11/28/98) measurements by M. Minty, J. Seeman
[65]log 9, p. 32 (12/7/98) measurements by W. Barry, J. Byrd, D. Li
[66]log 9, p. 32 (12/7/98) measurements by W. Barry, J. Byrd, D. Li

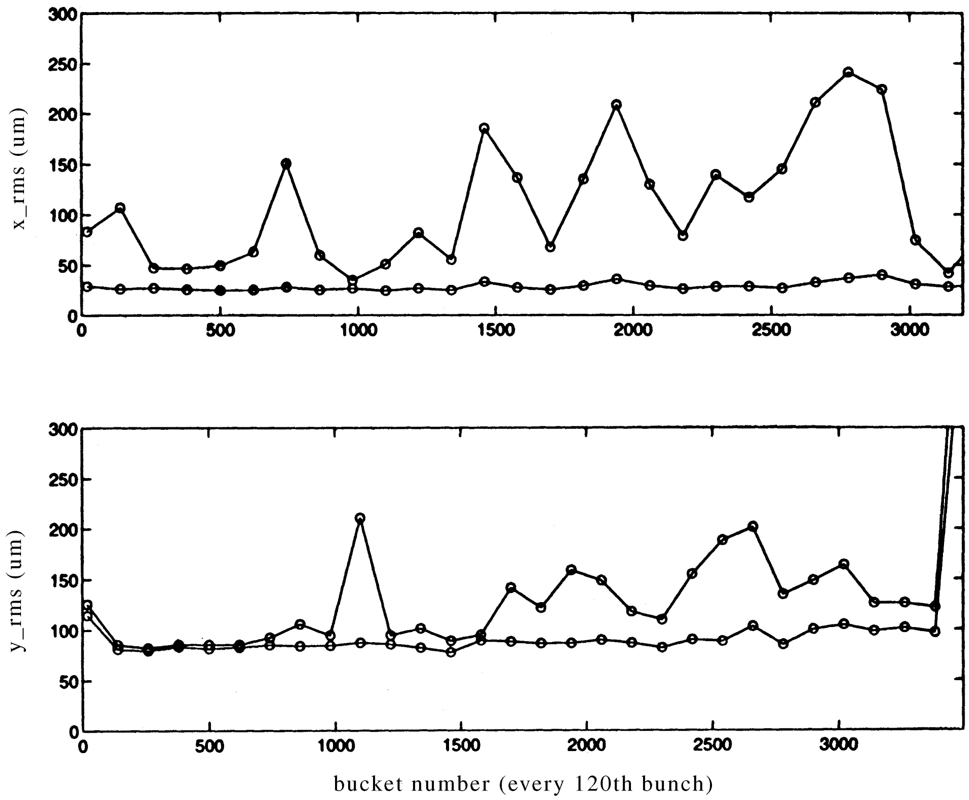

Figure 37: Residual horizontal motion detected at a BPM with nonzero dispersion after application of a cut on the longitudinal motion at the synchrotron frequency. The full scale corresponds to approximately 10 degree peak-to-peak phase excursion (at 476 MHz).

Late in the commissioning period, the longitudinal motion was measured using the bunch-by-bunch data acquisition system. Shown in Fig. 39 are the modal spectra obtained in three different measurements. In the first measurement[67] (top) with a 291-1 bunch fill, at about 210 mA there was no evidence of any higher-order mode instabilities, however, mode-0 was observed to oscillate with a variable amplitude of maximum 1 degree. In the second measurement[68] (middle), taken on the same day with a 291 even fill, an unstable mode, mode-127, with a threshold between 150-170 mA was detected. Mode-0 was identified to have a peak oscillation of about 1 degree as before. The final measurement[69] (bottom) taken under identical conditions showed a growth rate of the mode-127 of 0.045 ms^{-1} and a threshold of about 170 mA.

[67]log 9, p. 119 (12/14/98) measurements by J. Fox and S. Prabhakar
[68]log 9, pp. 124-129 (12/14/98) measurements by S. Prabhakar
[69]log 10, pp. 14-15 (12/15/98) measurements by D. Teytelman

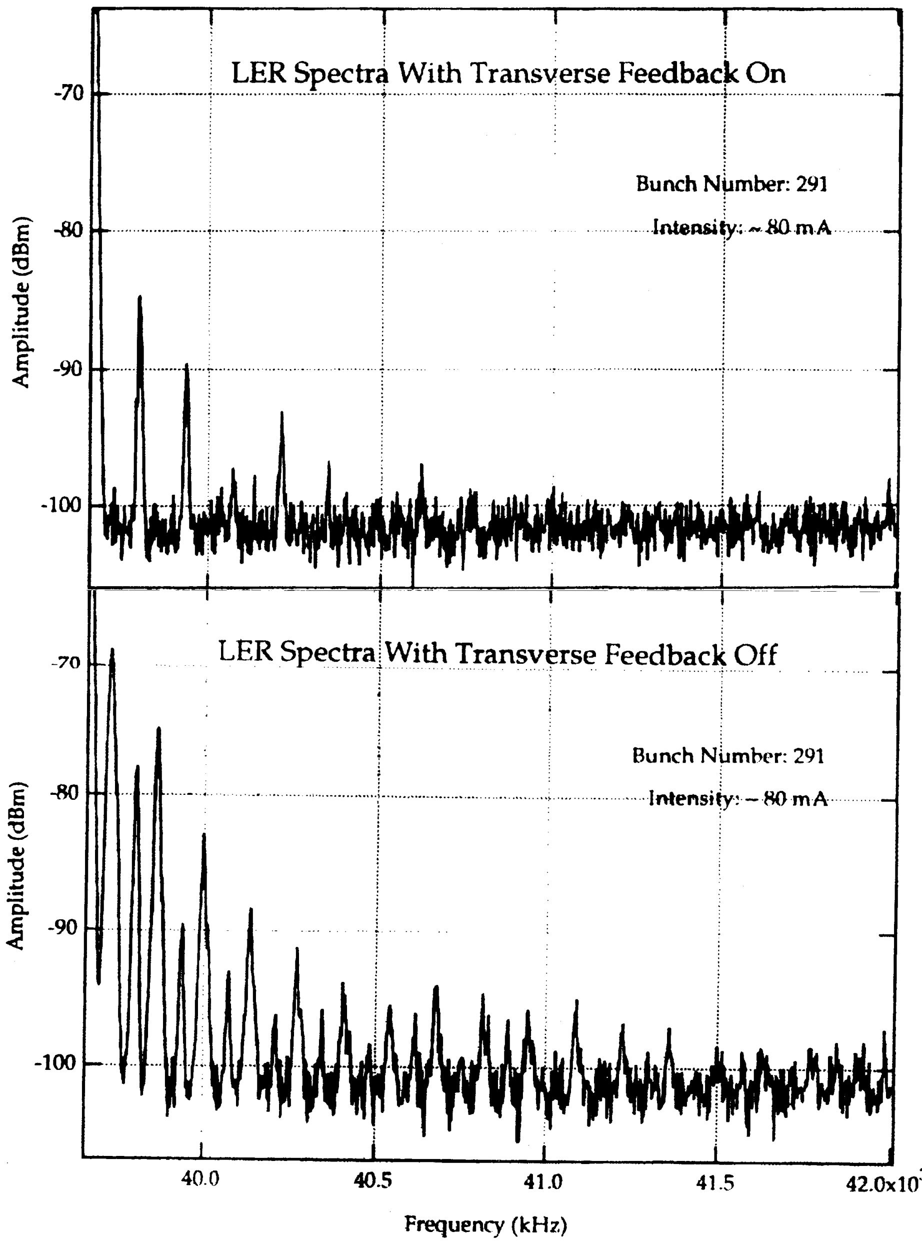

Figure 38: Vertical frequency spectra obtained with 291 bunches with transverse feedback on (top) and off (bottom). The total current was 80 mA.

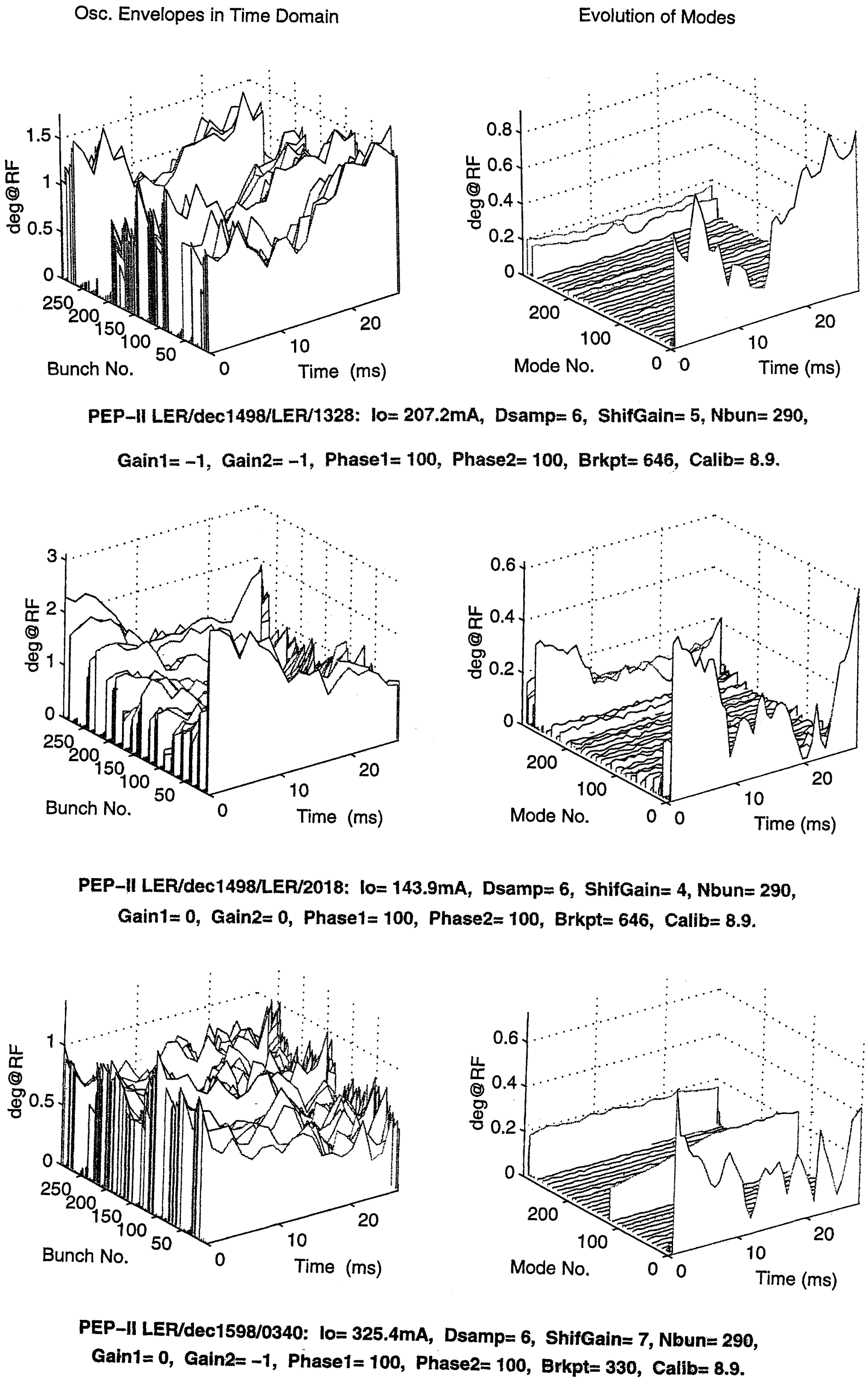

Figure 39: Longitudinal mode spectra from three separate measurements with 291-1 (top) bunches and 291 evenly spaced bunches (middle and bottom).

4.3 Bunch Trains

The beam current profile measured with variable length bunch trains is shown[70] in Fig. 40. The plots show the measured current distribution as a function of train length, spacing between trains, and total beam current as indicated. These interesting data await explanation.

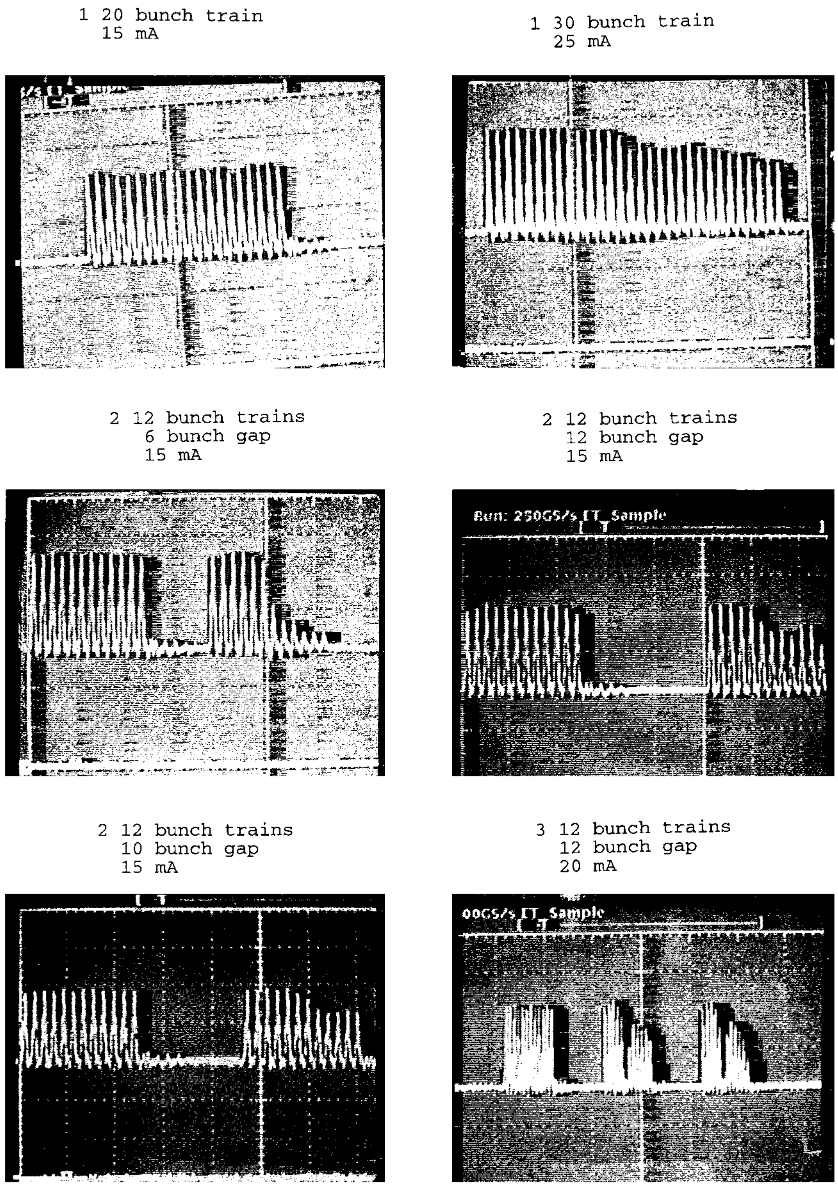

Figure 40: Bunch current monitor data showing measured current distributions as indicated.

[70]log 8, pp. 32-39 (11/27/98) measurements by W. Kozanecki, I. Reichel

Using a gate of width spanning approximately 20 buckets on the spectrum analyzer, data were acquired[71] as a function of position within the train as shown in Fig. 41. These data show two interesting features. First, towards the back of the train, the betatron tune line was observed to split into two lines. Secondly, towards the back of the train, longitudinal motion was also present on the beam as evidenced by the presence of synchrotron sidebands.

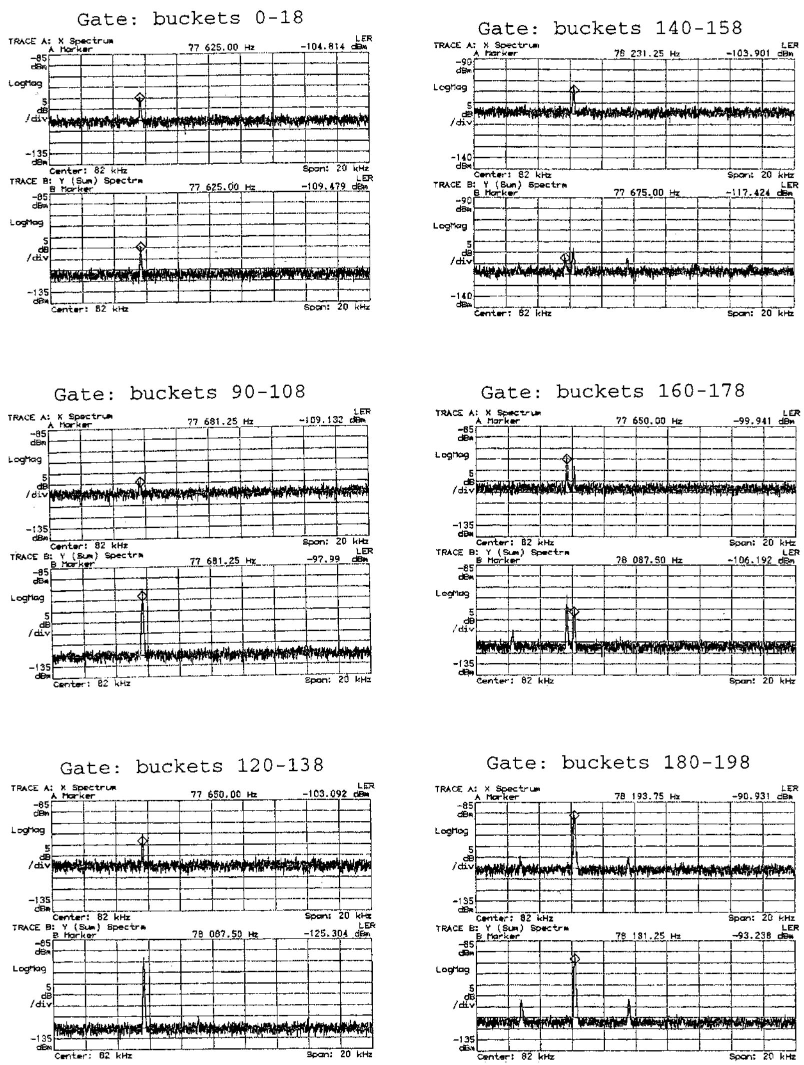

Figure 41: Spectrum analyzer data gated with a 20 bucket gate width sampled at different locations within a 100 bunch train with a 2 bucket bunch spacing.

[71] log 9, pp. 93-98 (12/13/98) measurements by A. Fisher

4.4 Other Measurements

The dependence of the transverse tunes on beam current was measured as shown in Fig. 42. The linear fits I_{sb} are $\frac{df_x}{dI_{sb}} = 78939 - 95.522 I_{sb}$ and $\frac{df_y}{dI_{sb}} = 86046 - 213.36 I_{sb}$ horizontally and vertically, respectively for the single bunch (sb) data. For the multiple bunch case, $\frac{df_x}{dI_t} = 79034 + 1.8 I_t$ and $\frac{df_y}{dI_t} = 86050 - 2.9 I_t$, where I_t is the total beam current.

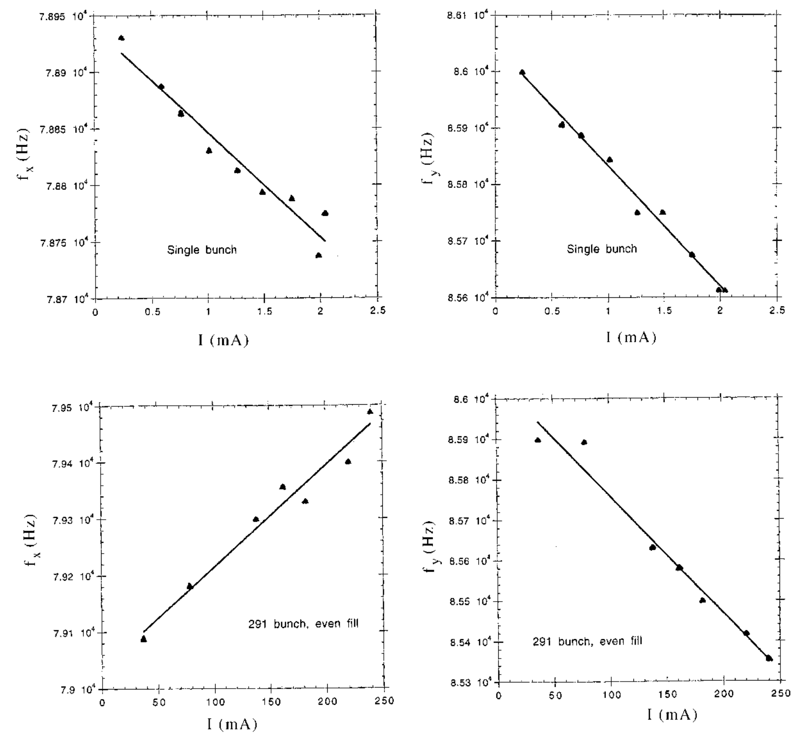

Figure 42: Tune shift with current measured with a single bunch (top) and with 291 bunches evenly distributed (bottom). The vertical axes give the horizontal f_x and vertical f_y frequencies for the beams' fractional tunes.

5 Summary and Outlook

It is hoped that the presented data acquired during the Oct-Dec, 1998 commissioning period may be useful for independent analyses and to stimulate further theoretical studies. While the intent of this report has been to compile recent observations without interpretation, a few general results may be drawn and outstanding mysteries may be highlighted.

The characteristic features of beam instabilities (including current thresholds, excitation frequencies, and growth rates) were found to be strongly dependent on the particular beam current distribution used. Most importantly for PEP-II physics research, beam instabilities were found to be significantly reduced in fill patterns, not unlike the design fill pattern, consisting of equidistant bunches (with a small gap) and with multiple bunches of modest single-bunch beam currents.

Specific experiments (see Appendix A) were performed to better understand the observed beam instabilities. In the electron accelerator, no evidence was found within a resolution of about 1-σ of instabilities arising from possible ion effects. While no specific experiments were performed to look for theoretically predicted electron cloud instabilities in the positron ring, curiously, bunch train dynamics experiments performed in both accelerators exhibited common instability characteristics in terms of beam loss thresholds.

In the more thoroughly studied high energy ring, a few anomalies became apparant in reviewing the data summarized in this report. First, with the design fill pattern and certain bunch train distributions, there was evidence of a high-multipole ($4\nu_x - 2$ and $3 - 4\nu_x$) resonance as observed using Fourier analysis of beam position monitor data (Fig. 24) and direct spectrum analyzer data (Fig. 17). Contrarily, not all spectra recorded under conditions of self-excited beam excitations revealed beam motion at these unexpected frequencies.

In the high energy ring, comparison with the high current (750 mA) commissioning run of January 1998 revealed[72] a significantly increased betatron tune shift with single-bunch beam current albeit with measurements over a larger range of single-bunch currents in the more recent measurements. The significance of this should be evaluated.

In the newly commissioned positron ring, transverse beam instabilities were observed to be minimal up to the maximum beam current allowable (under administrative constraints) of about 300 mA. However, significant longitudinal beam instabilities were observed with multiple-bunch beams. In addition to driven mode-0 longitudinal motion a singular higher order mode was diagnosed late in the commissioning period.

Measurements in both accelerators with bunch trains revealed unexpected behavior. In the electron ring, observed beam loss occuring towards the back of a train was directly correlated with large amplitude transverse oscillations. As the beam current was increased, the number of affected bunches was also observed to increase. Surprisingly, the measurements of the residual motion along the bunch train showed significantly larger amplitude excursions in the horizontal plane. In addition, as a function of distance along the train, the excitations appeared first in horizontal plane. In the positron ring, measured bunch current profiles also exhibited beam loss towards the back of the train. Whether or not the stability issues observed with bunch trains is important with more evenly spaced beam current distributions as called for under design operating conditions has yet to be determined.

This report on coupled-bunch-instabilities is lacking measurements in a number of significant areas. With the exception of a few measurements in the positron ring, longitudinal beam dynamics were not extensively studied. In fact, the longitudinal feedback systems were not routinely required in either accelerator during this commissioning period. In the high energy ring longitudinal beam dynamics studies seemed unneccessary and hence no measurements with a streak camera, for example, were motivated. Also not measured were either the longitudinal or transverse impedance as can be determined from beam transfer function measurements.

[72]known changes in the accelerator since January, 1998 include multiple modifications to the interaction region vacuum chamber, the addition of 'gasket collimators' with non-smoothed edges, and the addition of a high-current abort system with a circular-to-cylindrical vacuum chamber transition

These experiments are in development and may be useful in comparison with theoretical estimates. In the future, we anticipate gaining further understanding of coupled-bunch instabilities particularly if relevant for colliding beam operation.

Acknowledgments

The data presented in this report were made my numerous individuals whom I have tried to acknowledge appropriately throughout the text. Naturally, the improvements in diagnostic methods were made possible only after considerable offline studies. In addition to those persons noted, enormous thanks are due to A. Fisher (synchrotron light monitors, gated tune monitor, transverse feedback, and beam transfer function measurements), W. Barry, A. Young, and D. Anderson (for the bunch-by-bunch feedback systems), and M. Zelasny (for upgrades in the buffered data acquisition software). Also, invaluable contributions were made by and insightful discussions were benefited from greatly by Y. Cai, A. Chao, J. Dorfan, A. Fisher, S. Heifets, T. Himel, A. Hoffman, B. Richter, J. Seeman, U. Wienands, M. Zisman, and B. Zotter.

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[9] Y. Cai, M. Lee, and U. Wienands, 'Drifting of the Closed Orbit in the High-Energy Ring', SLAC-AP-114 (Dec, 1998).

Appendix A – Cross references to specific experiments

For brevity, the diagnostic methods used are abbreviated as follows: bunch current monitor (BIC), spectrum analyzer (SA), BPM rms using buffered data acquisition (BDAQ), and bunch-by-bunch data acquisition (BBB).

Baseline measurements

- HER threshold and characteristic frequencies: BBB with 18 bunch fill (vertical plane), pp. 4-8.
- HER threshold: BDAQ with 97 bunch fill (both transverse planes), pp. 10, 15-16.
- HER growth rates: BBB with 18 bunch fill (vertical plane), pp. 4-8.
- LER threshold: BDAQ with 97 bunch fill (both planes), p. 37.
- LER threshold: BDAQ with 97 bunch fill (both planes), p. 37.
- LER spectrum at 200 mA: BDAQ with 291 bunches, pp. 38-39; SA with 291 bunches at 80 mA, pp. 38,40.
- LER growth rates and characteristic frequencies: BBB with 291 bunches at about 200 mA, pp. 39-41.

Threshold versus β function

- HER: BBB with 18 bunch fill (vertical plane), pp. 4-6.
- HER: SA with 36 bunch fill (both transverse planes), p. 9.

Threshold versus beam size

- HER: SA with 45 bunch train, pp. 24, 26.
- HER: SA with 50 bunch train, pp. 24-25.

Effect of change in temperature of the Q2 beam pipe

- HER: BBB with 18 bunch fill, pp. 6-7.

Threshold versus beam steering

- HER: BDAQ with 97-10 bunch fill, pp. 11-13.
- HER: BBB with 97-10 bunch fill, p. 14.
- HER: BDAQ with design fill, p. 18.

Threshold versus chromaticity

- HER: 50 bunch train, pp. 23-24.

Motion along a bunch train

- HER: BIC and BDAQ variable length trains, pp. 20-23, 31-32.
- HER: BIC variable length trains, pp. 27-30.
- HER: SA with 20 bunch train, p. 27.
- LER: BIC with variable length trains, p. 42.
- LER: SA with 100 bunch train, p. 43.

Threshold and modal spectrum versus bunch length

- HER: BDAQ with 97 bunch fill, p. 16.

Power dissipation at IR12 collimators

- HER: thermocouples with 97 bunch fill, p. 16.
- HER: thermocouples with 291 bunch fill, p. 17.

Threshold measurements with distributed ions pumps on and off

- HER: BDAQ with a 50 bunch train, pp. 22-23.
- HER: BIC with a 50 bunch train, p. 23.
- HER: SA with a 100 bunch train, p. 23.

Threshold measurement versus ion-clearing voltage

- HER: ion-induced current with variable fill pattern, pp. 33-34.

Tune peak broadening

- HER: SA with 1,2,4,9,18, and 36 bunches at 1 mA total current, pp. 3-4.

Bunch-to-bunch transfer function measurements

- HER: SA, p. 3.

Effect of cavity detuning

- HER: BIC with 50 bunch train, p. 27.