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Observations of Bunch Lengthening Effects in the APS 7-GeV Storage Ring*

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Abstract

Measurements of the bunch length and horizontal beam size at a dispersive point in the lattice versus single-bunch current have been done on the Advanced Photon Source (APS) 7-GeV storage ring. These data are relevant to issues (limits) of obtaining higher volume charge densities for storage-ring-based FELs. Bunch lengths from $\sigma_\tau \sim 25$ to 70 ps were measured using a Hamamatsu C5680 dual-sweep streak camera. Additional complementary data on energy spread deduced from horizontal beam size at a dispersive point in the lattice were also tracked versus single-bunch current. Both optical synchrotron radiation (OSR) and x-ray synchrotron radiation (XSR) techniques were used. The significant bunch lengthening observed without a comparable horizontal size change (ΔE growth) is consistent with the potential well distortion model rather than the predictions of a microwave instability calculation. With higher rf gap voltage, peak currents up to 400 A were observed.

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DISCLAIMER

1. Introduction

There is increasing interest in obtaining shorter beam bunches and higher peak currents for enhancing gain for storage-ring-based free-electron lasers (FELs) [1]. Due to intrabeam scattering phenomena and other beam instabilities, there appear to be limits to what can be stably achieved in a storage ring (SR). As part of a program to probe the available parameter space for the Advanced Photon Source (APS) 7-GeV storage ring, investigations with a streak camera of bunch length versus single-bunch current were initiated early in the commissioning phase. Additionally, data were obtained on the transverse beam size images as a function of current at a horizontally dispersive point in the lattice. Using the calculated lattice values for the beta function (β_x) and dispersion (η_x), the observed beam size from optical synchrotron radiation (OSR) images was consistent with contributions of about (1) 115-120 μm from the emittance term, (2) a contribution of about 90 μm per 0.1% energy spread, and (3) the OSR imaging system resolution of about 65 μm. Initial assessments of these data were performed using both the potential-well distortion (PWD) model and a microwave instability model, and these are discussed. Data at higher rf gap voltages are also presented. Additionally, an interesting bunch-lengthening effect was observed during the multi-bunch operation near the operational limit of 100-mA stored beam for the available rf power at that time.

2. Experimental Background

The APS is a third-generation synchrotron radiation user facility for the hard x-ray community [2]. It has a low natural emittance of 8.2×10^{-9} m rad with 100-mA stored beam current. The nominal bunch length was projected at 50 to 100 ps, but operations have routinely achieved $\sigma \sim 40$ ps at 3 mA in a single bunch. Table 1 gives some of the key parameters for the storage ring. Besides the main rf frequency of 351.9 MHz and the damping times, the momentum compaction is positive, $\alpha = 2 \times 10^{-4}$.

One of the 40 sectors of the lattice is assigned for dedicated particle beam diagnostics. In the studies reported here, a dipole source of synchrotron radiation (both OSR and XSR) has been used to image the particle beam at a horizontally dispersive point in the lattice. With the nominal energy spread of 0.1%, a contribution of 92 μm is expected to be in quadrature with the nominal emittance term of 117 μm. For the OSR work, a Vicon charge-coupled device (CCD) video camera was used to image the transverse beam size. The OSR was transported by a series of flat mirrors and one spherical mirror to an optics table outside the accelerator tunnel enclosure. Subsequent to the October 1995 run, an in-tunnel x-ray pinhole station was used with a $CdWO_4$ converter crystal viewed by a Questar telemicroscope. Although the camera resolution at the converter screen for a calibration pattern was ~ 8 μm, the total system resolution (including the scintillator point spread function) with the magnification of about 0.4 was closer to 80 μm at the source.

The main features of the Hamamatsu C5680 dual-sweep streak system include a synchroscan sweep unit phase-locked to the 117.3-MHz source from the accelerator rf system oscillator. On its fastest range, it has a resolution $\sigma_{res} \sim 0.6$ ps with time jitter projected to be less than that. The four selectable ranges have a time axis span of 0.15 to 1.5 ns. Range 3 was generally used with a $\sigma_{res} \sim 5$ ps since the SR bunch lengths were observed to be greater than 20 ps. The slow sweep axis can be triggered at up to 10 Hz with a selection of time spans from 100 ns to 100 ms. For the single-bunch experiments with a ring circulation time of 3.68 μs, the 10-, 20-, and 100-μs ranges were usually used. The streak images were read out at the standard 30-Hz video rate using a Peltier-cooled CCD camera. Controls were done through a local, manual controller or a GPIB interface to the local computer. The video images were also shipped via the video mux to the main control room for on-line display on TV monitors. On-line analyses of the image full width at half maximum of intensity (FWHM) for the temporal direction were performed. Off-line analysis involved fitting the temporal profiles to a Gaussian shape. For the purposes of comparison, the 1-sigma (σ) value of the distribution is found by dividing the FWHM value by 2.35.

3. Results

Measurements of the beam bunch lengths were initially done at an rf gap voltage below the planned operational level due to rf power limitations in the commissioning phase. Four different sets of data have been taken with two of them also having the complementary horizontal beam size tracking done as well.

An example of the dual-sweep streak camera data is shown in Fig. 1. In this case the vertical axis is the fast-time axis and the horizontal axis spans 10 μs. Due to the OSR image rotation in the optics before the streak camera, the y spatial profile is also recorded along the horizontal display axis. The three images correspond to three passes of the single bunch through the bending magnet. At a current of 3 mA, the bunch length is about 102 ps (FWHM) or 43 ps (σ). Figure 2 shows the bunch length variation from 30 ps (σ) at low current to about 70 ps (σ) taken at different effective rf gap voltages. All beam profiles were fit to a Gaussian shape. The August 19, 1995 data are first discussed. As a check on the signal levels, an ND 1.0 filter was used to attenuate some of the 5-mA images to effectively simulate 0.5-mA signal strength. The observed bunch lengths were within 10% of the unattenuated data indicating the space charge effects in the streak tube were not blurring the bunch length measurement. The rf gap voltage was about 6.5 MV based on the cavity probe calibration at that time. The bunch lengthening evaluated in terms of the Chao-Gareyte parameter followed the nominal one-third power dependence after about 1 mA [3]. Modeling of the effects was performed with the code ZAP [4,5], and a ring impedance $Z/n \sim 0.5\ \Omega$ was inferred. Additional modeling was done using both the PWD model and a microwave instability model. The microwave instability calculation predicted a significant increase (2 to 3 times) in energy spread of the beam from the nominal 0.1% value while the PWD model would predict no increase in energy spread with beam current.

The next set of data in October 15, 1995 was taken at a synchrotron frequency of only 1.3 kHz (indicating an rf gap voltage <6 MV). Additionally, the rms horizontal size was tracked and was observed to be basically unchanged from 0.2 to 6 mA even though the rms bunch length approximately doubled [6]. This was done with OSR imaging. These data are consistent with the PWD model.

A third set of bunch length data at near 9-MV rf gap voltage (1.8 kHz synchrotron frequency) from March 14, 1996 can be compared to the two earlier sets in Fig. 2. Although other factors are perhaps involved, we succeeded in injecting over 43 nC into a single bunch corresponding to 12 mA average current. Using the standard relationship that peak current I_{pk} is given by

$$I_{pk} = \frac{Q}{\sqrt{2\pi}\sigma_t}, \tag{1}$$

where Q is the microbunch charge and σ_t is the rms bunch length for a Gaussian longitudinal charge distribution; this corresponds to about 300 A.

In Fig. 3, the data are plotted versus the Chao-Gareyte parameters. The change in slope at $\xi \approx 1.0$ is noted and may indicate a ring impedance lower than 0.5 Ω. The zero-current bunch length expected for APS is given in Ref. 6. The earlier data on October 1995 with the ~35 ps low-current bunch length (squares) seems reasonable, but the 8.7 MV data do not reach the expected 20 ps value. The streak camera was not run on its fastest range (0.6 ps resolution) but at about 5 ps resolution. This value is still much smaller than the observed sizes when evaluated in quadrature.

Although an estimate of the actual dispersion in the source point in the dipole magnet was made by tracking nearby rf BPM readings with rf frequency changes, a final direct measurement with the x-ray pinhole imaging system was done. The beam profiles (fit to a Gaussian shape) and the shift in observed position with changes in energy (rf frequency) from -0.5% to +0.5% are shown in Fig. 4. The lower part of the figure shows the result of 74 μm/0.1% ΔE. In Fig. 5, the rms beam size and bunch length for single-bunch currents up to 18 mA were tracked. It is noted that with this initial x-ray pinhole data, the limiting spatial resolution of 80-90 μm is larger than the OSR data case and partially reduces our sensitivity to energy spread changes. These data up to ~ 12 mA still exhibit no significant increase in horizontal size that could be attributed to large energy spread growth. Another feature to note is the peak current of about 400 A for these conditions (the diamond symbol uses the right-hand axis scale). Bunch lengthening seems to balance partially the increased charge injected into the bunch.

One other interesting bunch lengthening effect, although in multi-bunch mode, was observed during our first attempts to store 100 mA, the baseline design goal. With a limited rf gap voltage and power, the dual sweep streak images at ~ 99 mA and 101 mA were markedly different. The 99-mA data image had a bunch length (averaged over many bunches) of 70 ps (FWHM), but the 101-mA file showed

170 ps (FWHM). This was also at the limit of being able to inject additional beam. Even though each individual micropulse had less than 1 mA of current in it (and bunch length of about $\sigma \sim 30$ ps would be expected), it appears that a multibunch instability threshold was crossed in a narrow current range.

4. Summary

In summary, a series of experiments have been performed over the initial 12-month commissioning period of the APS storage ring. At the moment, these data show significant bunch lengthening with increased single-bunch current, but without comparable change in energy spread. These observations are more consistent with the PWD model and not the microwave instability explanation as applied to phenomena at Super-ACO and ALS [7]. Further studies with higher rf gap voltage and with positron beams are planned. It is expected that now there are dual-sweep streak camera investigations underway in four to five storage rings around the world, a more complete understanding of bunch lengthening phenomena will result [8]. This could be applied to operations and planning for storage-ring-based FELs.

5. Acknowledgments

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References

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Figure Captions

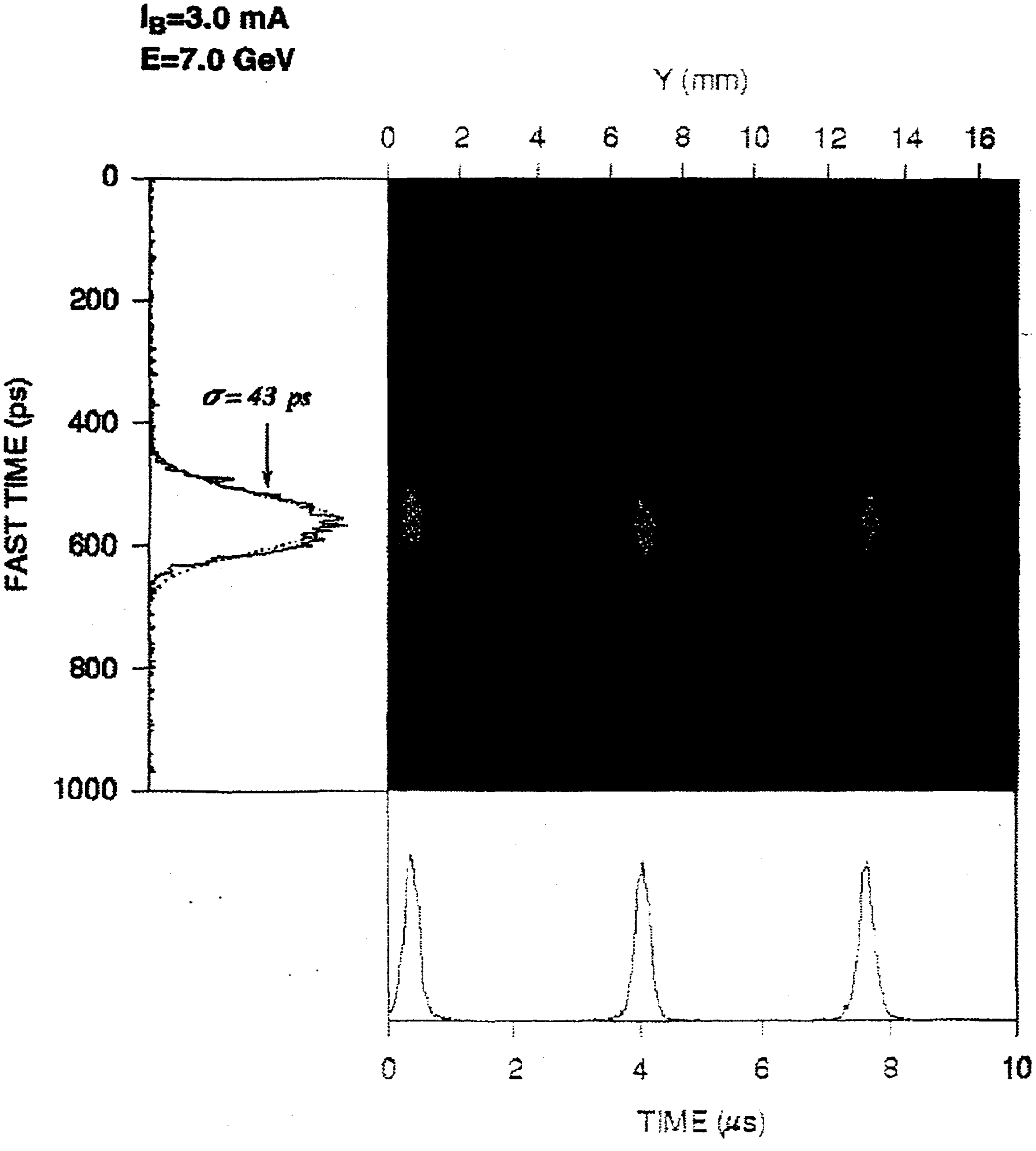
Fig. 1. Example of a dual-sweep streak image of a single bunch in the APS storage ring.

Fig. 2. Comparison of bunch length versus single-bunch current for three different runs and gap voltages: August 19, 1995 (squares), October 15, 1995 (triangles), and March 14, 1996 (circles). All profiles were fit to Gaussian shapes off-line. The March 1996 data involve the highest rf gap voltage, and a peak current of about 300 A was obtained.

Fig. 3. Plot of the four sets of bunch length data in terms of the Chao-Gareyte scaling parameter ξ in units of mA/GeV.

Fig. 4. Measurement of the dispersion in the bending magnet source point. The change in rf frequency was used to affect the beam energy and the beam image position was tracked.

Fig. 5. Measurement of rms beam size and bunch length versus single-bunch current (June 30, 1996 data). Up to 18 mA in a single bunch were attained corresponding to a peak current near 400 A. In the lower half of the figure, the triangle symbol is for bunch length (left-hand axis) and the diamond symbol for peak current (right-hand axis).



I_B=3.0 mA
E=7.0 GeV
Y (mm)
0 2 4 6 8 10 12 14 16
FAST TIME (ps)
0
200
400
600
800
1000
σ= 43 ps
0 2 4 6 8 10
TIME (μs)

Fig. 1

APS SINGLE BUNCH LENGTH VERSUS BUNCH CURRENT

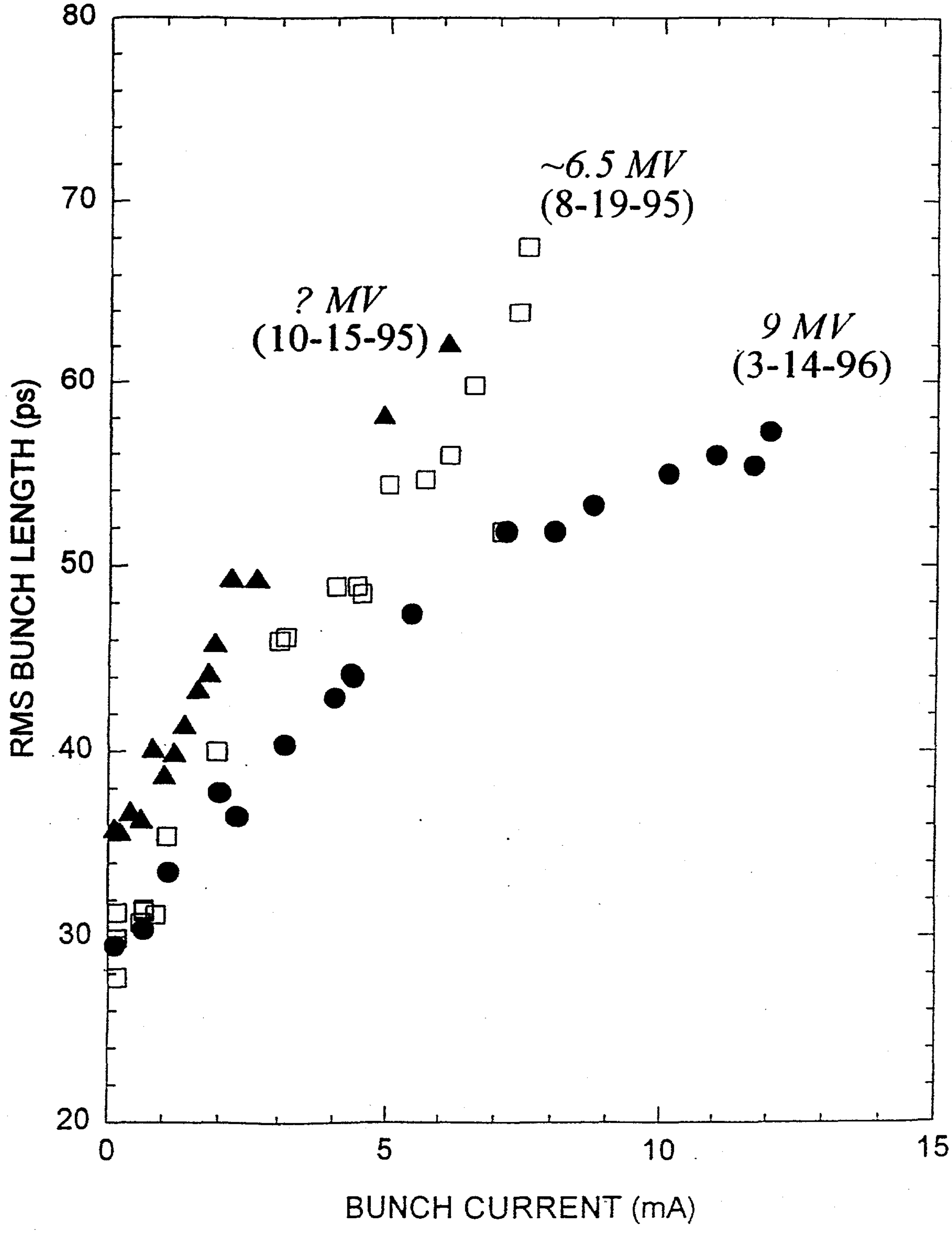


Fig. 2

APS SINGLE BUNCH LENGTH VERSUS BUNCH CURRENT

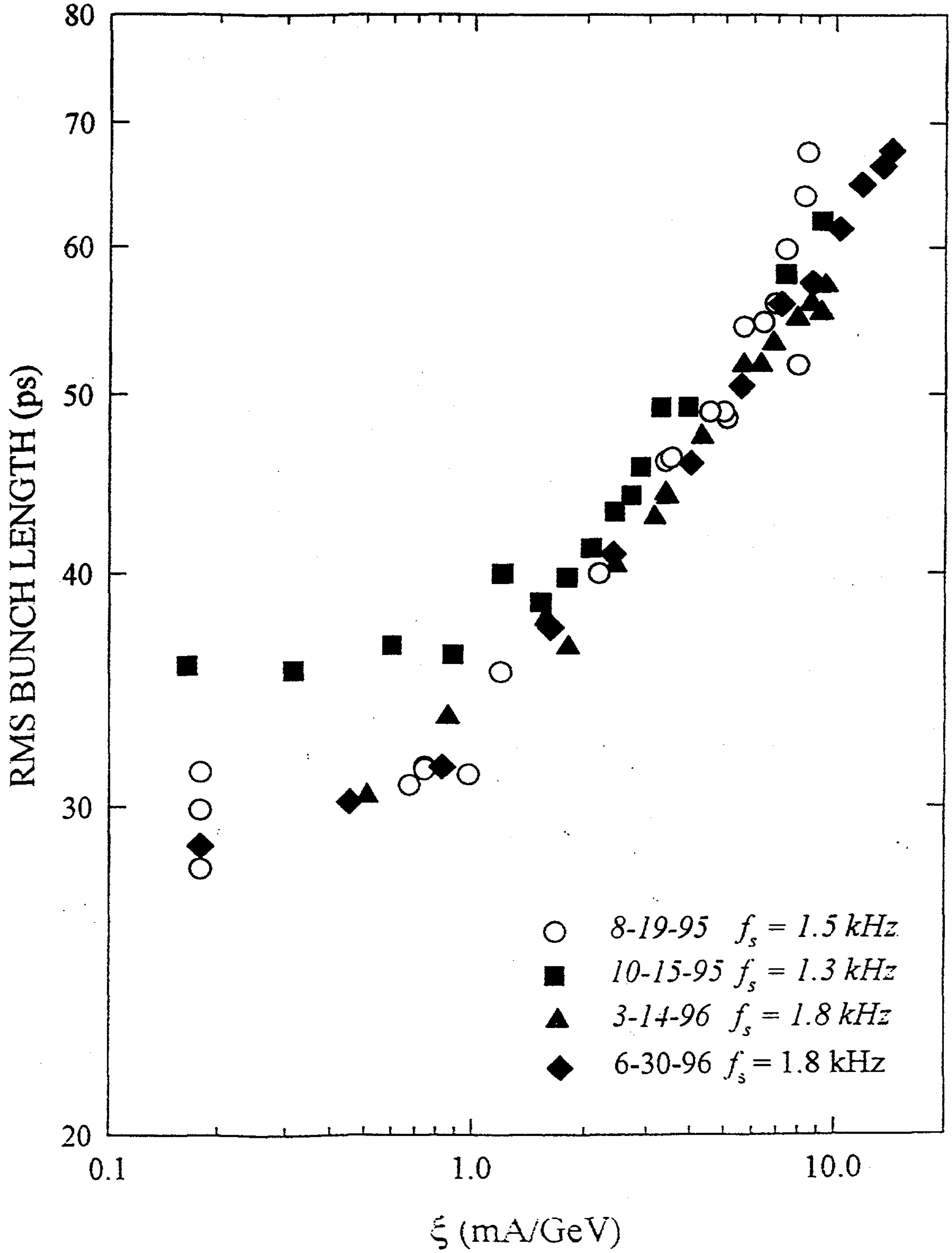
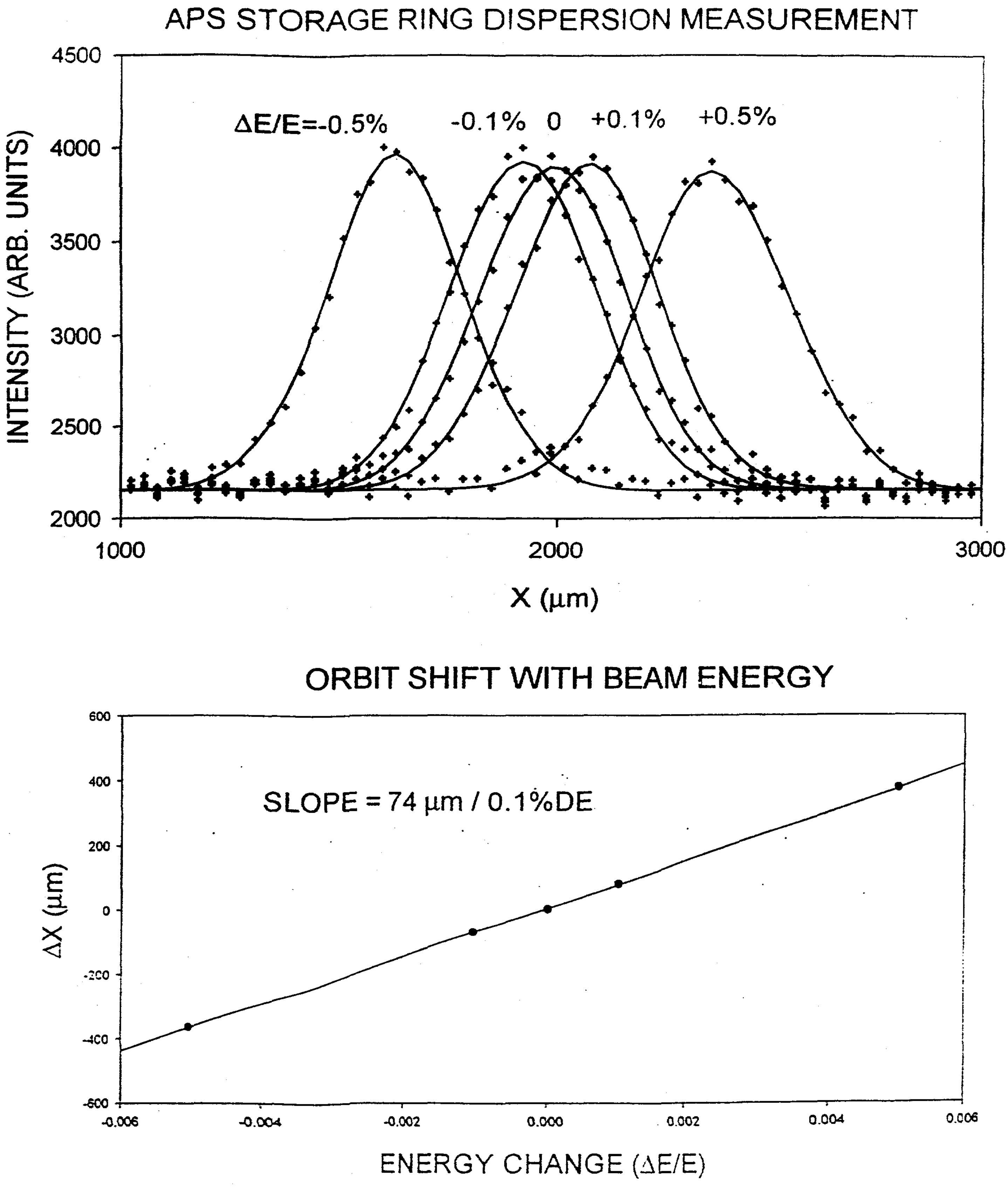
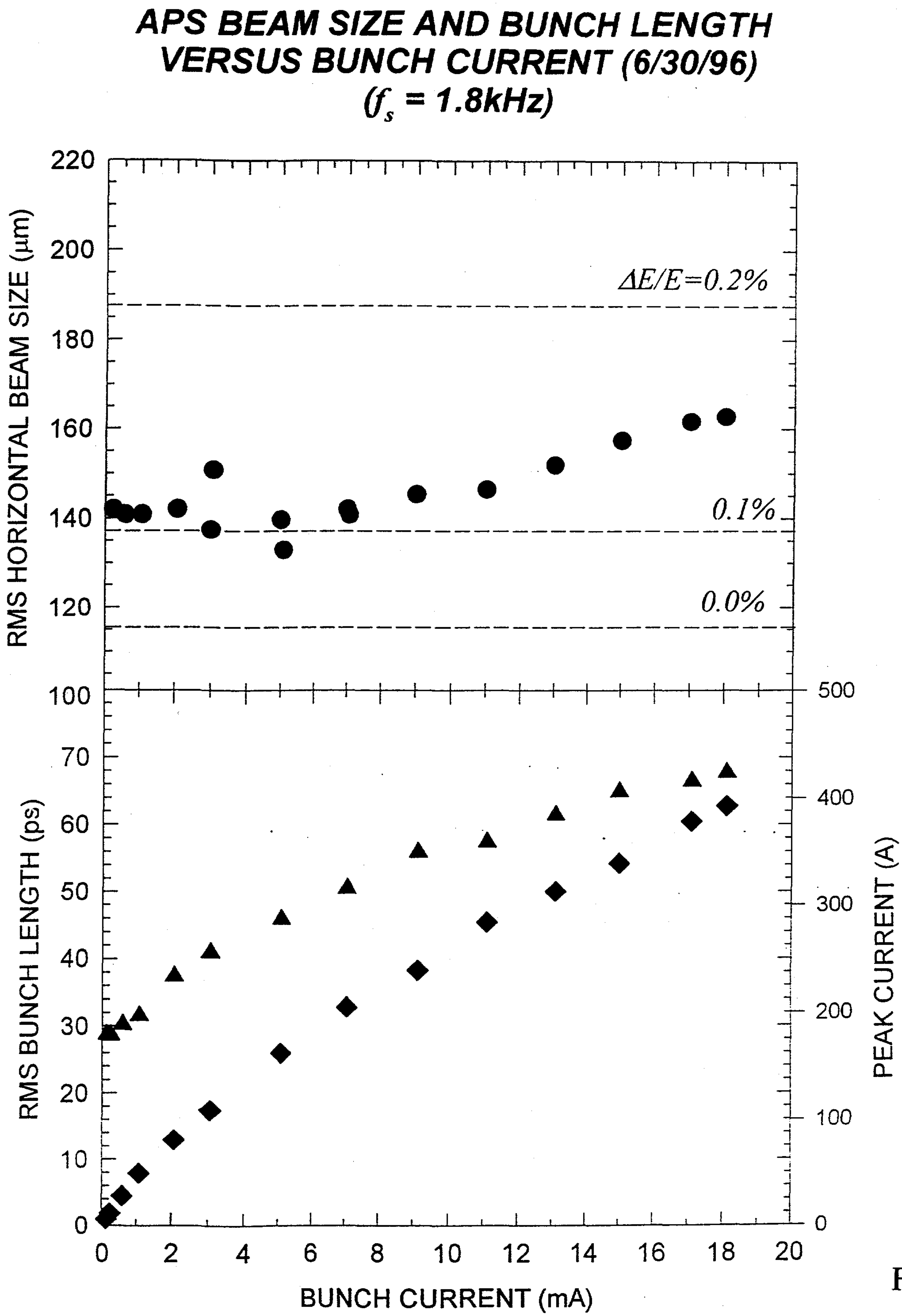


Fig. 3



APS STORAGE RING DISPERSION MEASUREMENT
INTENSITY (ARB. UNITS)
4500
4000
3500
3000
2500
2000
ΔE/E=-0.5%
-0.1%
0
+0.1%
+0.5%
1000
2000
3000
X (μm)
ORBIT SHIFT WITH BEAM ENERGY
SLOPE = 74 μm / 0.1%DE
ΔX (μm)
600
400
200
0
-200
-400
-600
-0.006
-0.004
-0.002
0.000
0.002
0.004
0.006
ENERGY CHANGE (ΔE/E)

Fig. 4



APS BEAM SIZE AND BUNCH LENGTH
VERSUS BUNCH CURRENT (6/30/96)
(f_s = 1.8kHz)
RMS HORIZONTAL BEAM SIZE (μm)
ΔE/E=0.2%
0.1%
0.0%
RMS BUNCH LENGTH (ps)
PEAK CURRENT (A)
BUNCH CURRENT (mA)

Fig. 5