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Streak Camera Measurements of the Longitudinal Distribution of a Single Bunch in CESR

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Abstract

Measurements of the beam's bunch length in the Cornell Electron-Positron Storage Ring (CESR) were made using a streak camera. The experimental set up and the analysis techniques used are described in this paper. For a single bunch in CESR, the dependence of the longitudinal distribution on the bunch current and accelerating RF voltage, was measured and compared with a simple theoretical model of the CESR vacuum chamber impedance. Some basic parameters of this model were determined from the measured bunch distributions presented in this paper.

1 EXPERIMENTAL SET-UP AND ANALYSIS TECHNIQUE

The streak camera uses synchrotron radiation produced by the accelerator dipole magnets to determine the longitudinal bunch distribution. The synchrotron light pulse is transported from the source, out of the vacuum chamber, to a safe location shielded from radiation, where the streak camera measurements can be made.

The longitudinal profiles of the beam distribution are fit to an asymmetric Gaussian function with a constant background given by

$$I(z) = I_0 + I_1 \exp\left\{-\frac{1}{2}\left(\frac{(z-\bar{z})}{(1+\operatorname{sgn}(z-\bar{z})A)\sigma_z}\right)^2\right\}$$

where I_0 is the pedestal, and I_1 is the peak of the asymmetric Gaussian. The term $\operatorname{sgn}(z-\bar{z})A$ is the asymmetry factor that parameterized the shape of this Gaussian.

2 CESR SINGLE BUNCH DYNAMICS

The longitudinal phase space in the storage ring is determined from accelerator components as well as from collective effects. In CESR, the electromagnetic fields which affect the bunch distribution are from the more than four hundred magnets, which guide the bunches around the accelerator, two RF accelerating stations, to counteract the bunch energy loss due to synchrotron radiation, and two wiggler magnets used to create synchrotron radiation for the CHESS X-ray Facility. Ignoring collective effects, the standard deviation bunch length is given by [1]

$$\sigma_\tau = \left\langle \tau^2 \right\rangle^{1/2} = \frac{\alpha}{\Omega_s}\sqrt{C_q E_0^2\left(\frac{I_3}{2I_2+I_4}\right)}$$

where I_2, I_3, and I_4 are the synchrotron integrals. The term α is the momentum compaction, E_0 is the nominal energy, and Ω_s is the synchrotron frequency. The synchrotron integrals that reflect CESR, when the streak camera experiments were performed, are denoted in Table 1.

The longitudinal distribution at low current is valuable to minimize collective effects and gives the opportunity to compare the CESR model with the time calibration of the streak camera. The results of the streak camera measurements at low current (Table 2) can be compared with the CESR model (Table 1). There is a systematic difference between the CESR model and the measured values. The theoretical bunch length is 3.3% smaller than the measured bunch length when the wiggler magnets are closed, and 2.1% smaller than the measured bunch length when the wiggler magnets are open. A single snap shot of the bunch distribution with the wiggler open and closed is shown in Figures 1 (a) and (b).

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	Wigglers Open	Wigglers Closed
I_1	$8.791m$	$8.791m$
I_2	$9.336x10^{-2}\,m^{-1}$	$1.047x10^{-1}\,m^{-1}$
I_3	$1.716x10^{-3}\,m^{-2}$	$2.372x10^{-3}\,m^{-2}$
I_4	$2.088x10^{-3}\,m^{-1}$	$2.744x10^{-3}\,m^{-1}$
I_5	$3.890x10^{-4}\,m^{-1}$	$5.386x10^{-4}\,m^{-1}$
U_0	$1.0290MeV$	$1.1541MeV$
$\frac{\sigma_E}{E}$	$6.115x10^{-4}$	$6.782x10^{-4}$
σ_Z	$1.565x10^{-2}\,m$	$1.739x10^{-2}\,m$

Table 1. The synchrotron integrals for CESR for the case when the wiggler magnets are open (CHESS is not collecting data) or closed.

Wigglers	RMS σ_z(mm)	Asymmetry Factor
Closed	17.89 ± 0.35	-0.020 ± 0.022
Open	15.91 ± 0.12	-0.0024 ± 0.029

Table 2. The CESR low current bunch length results with wiggler magnets open and closed.

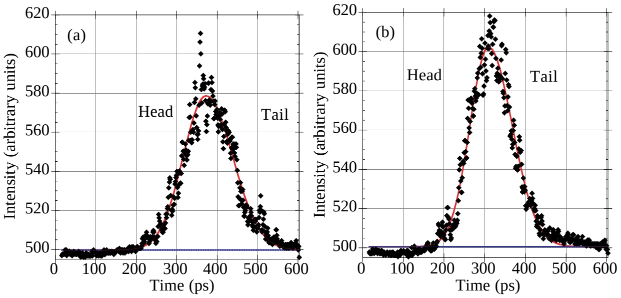

Figure 1. A single data acquisition of the bunch distribution in CESR with: (a) the wiggler magnets closed at a current of 1.4 mA. (b) The wiggler magnets open at a current 1.4 mA.

At low current, the collective effects for the bunch are small. As a result, the equilibrium bunch length in a storage ring is inversely proportional to the square root of the RF accelerating gap voltage. At low current the electron bunch length in CESR was measured as a function of RF accelerating voltage. The mean and root mean error were calculated at each RF setting and plotted in Figure 2(a). Fitting the data to the function $\sigma_z = A(V_{RF})^m$ gives a value of $m = -0.43 \pm 0.02$.

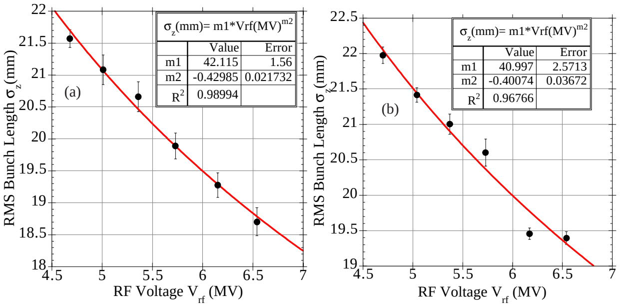

Figure 2. The bunch length as a function of RF accelerating voltage when the current in CESR is (a) 3.20 mA and (b) 15.00 mA.

The measurement was also made at high current. The mean and root mean error were calculated at each RF setting and plotted in Figure 2(b). Fitting the data to the function $\sigma_z = A(V_{RF})^m$ gives a value of $m = -0.40 \pm 0.04$.

Comparing the low and high current results, it can be concluded that the dependence of the bunch length, on the RF accelerating voltage, does not change as the current changes in CESR and m<0.5.

3 CESR HIGH CURRENT MEASUREMENTS

The electron bunch distribution was measured for currents from 1 mA up to 35 mA with wigglers open and closed. A plot of the bunch length and asymmetry factor, as a function of current, with the wigglers open and closed is shown in Figures 3 and 4.

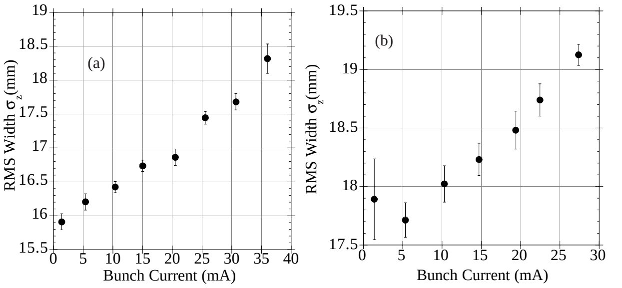

Figure 3. The bunch length in CESR as a function of current for wiggler magnets: (a) open and (b) closed.

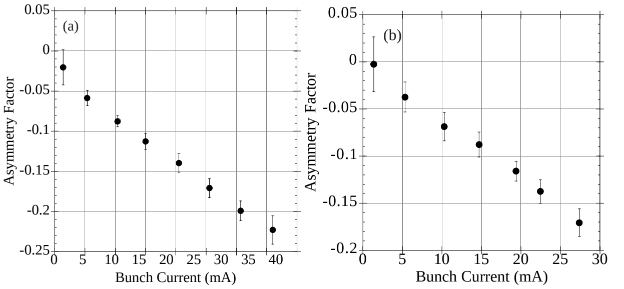

Figure 4. The asymmetry factor as a function of current in CESR for wiggler magnets: (a) open (b) closed.

There are several noteworthy features of the experimental data: 1) There is a 12% growth in the bunch length between the currents from 1 to 30 mA. 2) The asymmetry factor (shown in Figures 4 (a) and (b)), which measures the departure from a Gaussian distribution, increases in both cases as a function of current. The asymmetry factor is linear with current, whether the wigglers are open or closed. 3) The tail of the distribution gets longer as the current increases, which is a signature of potential well distortion due to the resistive impedance of the vacuum chamber. Figures 5 (a) through (c) are single data acquisition, at three different currents, fit to an asymmetric Gaussian function. These distributions can be used to determine the vacuum chamber impedance of CESR.

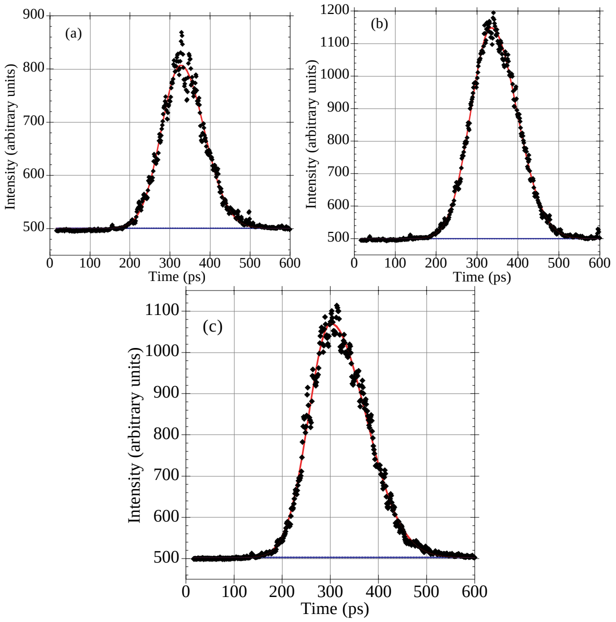

Figure 5. A single data acquisition of the CESR bunch distribution when the wiggler magnets are open, and a single bunch current is (a) 5.40 mA, (b) 15.0 mA, and (c) 30.5 mA.

4 CESR IMPEDANCE

In the same manner that the RF accelerating fields affect the bunch distribution, beam induced voltages from longitudinal wakefields also influence the shape of the bunch distribution [2,3]. With potential well distortion, the bunch distribution is static but distorted from a Gaussian distribution by the beam induced voltage. We observe in CESR a greater distortion for higher beam current. Assuming that the bunch's wakefield may be parameterized by

$$V_w(t) = RI_b(t) + L\frac{dI_b(t)}{dt},$$

the charge distribution can be determined numerically by integration [3]. Under the assumption that the resistance and inductance are constant over the measured range of bunch lengths, the resistive and inductive impedance components of the CESR storage ring vacuum chamber are determined from a χ^2 fit between the measured bunch distributions and the simulated bunch distributions. The χ^2 fit is given by

$$\chi^2 = \sum_{i=1}^{n} \frac{\left(S(t_i) - M(t_i)\right)^2}{S(t_i)}$$

where $S(t_i)$ and $M(t_i)$ are the simulated and measured bunch height at time t_i in the distribution. From the minimum χ^2 fit the resistance and inductance for each current setting are inferred to be

$$R_{open} = 1523 \pm 343\Omega \text{ and } R_{closed} = 1322 \pm 310\Omega$$

and

$$L_{open} = 65 \pm 12nH \text{ and } L_{closed} = 72 \pm 13nH.$$

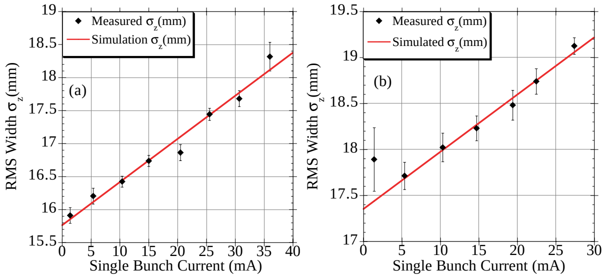

Figure 6. The measured and simulated bunch length as a function of current when the wiggler magnets are (a) open and (b) closed.

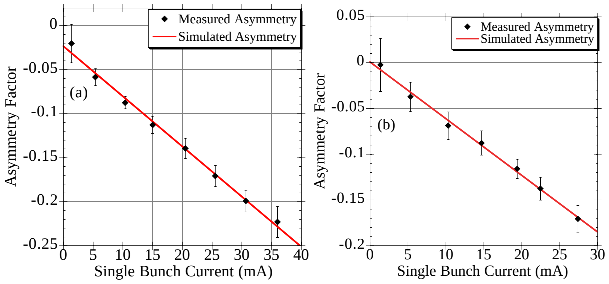

Figure 7. The measured and simulated bunch asymmetry as a function of current when the wiggler magnets are (a) open and (b) closed.

The uncertainties were determined by varying the simulation over the range of measurement errors on the asymmetry factor and rms width. Comparisons between the simulated bunch distributions using the above resistance and inductance and the streak camera measurements are shown in Figures 6 and 7.

5 CONCLUSION

In this paper, we have reported the results from the single bunch streak camera measurements that were done for the first time at CESR. These experiments allowed us to resolve the details of the beam distribution not available by other techniques. We have also established that the potential well distortion is the main single bunch collective effect in CESR. It leads to some asymmetry and lengthening of the beam distribution at high current. We have looked for single bunch coherent instabilities but have not registered any up to the highest value of current allowed by the CLEO detector background thresholds. Finally we have also established that the wiggler magnet changes the synchrotron integrals, as expected, resulting in a change in bunch length.

The low current single beam bunch length measurements are in close agreement with a simple theoretical model of CESR. The bunch length growth with current, when the wiggler magnets were closed and opened, was used to determine the impedance of CESR, in this model.

The assumption that the resistive and inductive impedance is constant, over the bunch lengths measured, is consistent with the results. The impedance was determined by comparing the measured bunch length dependence on the current and comparing it to simulations. With this method, the vacuum chamber impedance has a resistance of $1523 \pm 343\Omega$ and $1322 \pm 310\Omega$ and an inductance of 65 ± 12nH and 72 ± 13nH for the case of the wiggler magnets open and closed, respectively.

These measurements confirm our understanding of the theoretical model of the CESR and were valuable in exploring the possible future usage of streak cameras as a diagnostic tool in the CESR accelerator complex.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

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