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Longitudinal Wake Potential Measurement on the Cornell Electron-Positron Storage Ring*

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Abstract

This paper describes a method for measuring the longitudinal wake potential of the Cornell Electron-Positron Storage Ring (CESR). The longitudinal wake potential was determined by measuring the time delay between successive bunches as a function of current. The slope of the wake potential was determined by the changes in the bunch length as a function of bunch current. A theoretical description of the experiment and the measurements performed is provided in this paper.

1. Introduction

When a bunched beam passes through an RF cavity, a disk loaded wave-guide, transitions in the vacuum chamber, or other accelerator components, it can radiate significant electromagnetic fields. These fields, called wakefields, remain in the chamber after the bunch's passage and are able to act back on the bunch, to produce generally undesirable effects such as a net energy loss or energy transfer from head to tail of the bunch or act on subsequent bunches by transferring energy or changing the longitudinal distribution. In the extreme case the wakefield can make the beam unstable. In the longitudinal direction it is more convenient to speak of a wake potential rather than wakefield. The strength and temporal response of the wake potential depends on the shape of the many vacuum chamber elements in the accelerator.

This paper describes an experimental study of the longitudinal wake potential at CESR in the spring of 1997 before any superconducting cavities were installed. The determination of the longitudinal wake potential is based on the measurements of timing delays between bunches of varying spacings in CESR to determine the strength of the wake potential. The slope of the wake potential is likewise determined from bunch length measurements using a streak camera.

2. Theoretical Description

The longitudinal wake potential is determined by measuring the phase (time) shift between bunches as a function of current in the following manner. Three bunches are

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injected into the CESR storage ring with the bunch spacing shown in fig. 1. The precursor bunch has a current of 2mA and is located one RF bucket in front of the main bunch. The main bunch current during the experiment is either 5 or 20mA and is located a variable time δt in front of the 5mA trailing bunch. By measuring timing difference between the precursor bunch and the trailing bunch as the main bunch current is varied, the longitudinal wake potential can be determined.

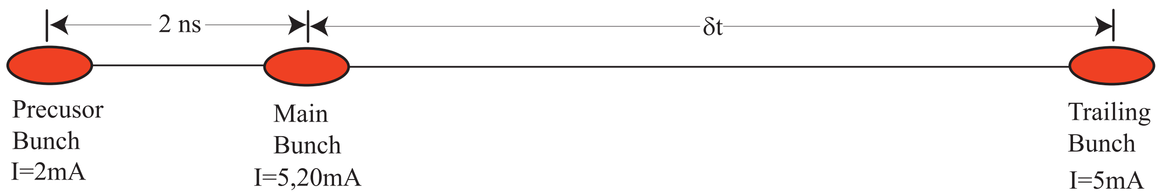

FIG. 1 (color). The bunch spacing for the three bunches in the longitudinal wake potential experiment. The precursor bunch arrives at locations in CESR at an earlier time than the trailing bunch. The time difference between the precursor bunch and main bunch is two nanoseconds and the time difference between the main bunch and the trailing bunch, δt, is varied between 2 to 56ns.

Consider three closely spaced bunches circulating in a storage ring. The time differences between the three bunches is current dependent and changes due to the applied voltage (accelerating RF voltage) and induced voltages (beam loading of the fundamental mode of RF cavities, higher order mode loss, and longitudinal potential), imposed on each bunch. From this time change the longitudinal wakefield can be measured.

For the precursor and trailing bunches, the time delay can be calculated from a phasor diagram of the interaction between the beam, the storage ring vacuum chamber, and the RF system [1]. A detailed calculation of the theory can be found elsewhere while this paper will concentrate on the description and analysis of the measurement[2].

For the analysis, several simplifications are made: 1) The RF system regulates the RF power such that the average cavity voltage is constant. 2) The precursor and trailing bunch are low current, so higher current affects such as higher order mode loss are small for them but the effects are included in the calculation[2].

The time shift between the precursor and trailing bunch due to a current change in the main bunch is given by[2]

$$\delta t = \frac{V_{wake} + V_b}{\omega_{rf} V \sin\varphi_0} \tag{1}$$

where ω_{rf} is the RF angular frequency, V_{wake} is the longitudinal wake potential, V_b is the RF cavities fundamental beam loading voltage, V is the average RF voltage, and φ_0

is the synchronous phase. Knowing the time shift between the precursor and trailing bunch allows the longitudinal wake potential to be determined for various bunch spacings.

The bunch length for an isomagnetic storage ring is given by [3]

$$\sigma_\tau = \sqrt{\frac{2\pi C_q \alpha R E_0^2}{\left(mc^2\right)^2 J_\varepsilon \rho_0 \dot{V}}}$$

where $C_q = 3.84 \times 10^{-13}\,\mathrm{m}$, α is the momentum compaction, R is the radius of the ring, E_0 is the nominal energy, J_ε is the energy partition number, ρ_0 is the radius of curvature, and $\dot{V}$ is the slope of the total voltage ($V = V_{RF} + V_{wakefield}$ and $\dot{V} = \dot{V}_{Wake}$). The change in the bunch length can be written in terms of the change in the wake potential voltage as

$$\frac{\Delta\sigma_\tau}{\overline{\sigma}_\tau} = -\frac{\Delta\dot{V}_{Wake}}{2\overline{\dot{V}}_{Wake}} \tag{2}$$

where $\overline{\sigma}_\tau$ is the average bunch length and $\overline{\dot{V}}_{Wake}$ is the average slope of the wake potential voltage. The average slope of the wake potential voltage can be concluded from the bunch length measurements with the streak camera.

3. Experiment and Analysis

The experiment was done in the following manner:

(I) Three bunches of electrons were injected into CESR with the current for the precursor bunch at 2mA and main and trailing bunches at 5mA. As denoted in fig. 1, the precursor bunch is one RF bucket (2ns) in front of the main bunch and the time delay between the main and trailing bunch was varied. For the first measurement the trailing bunch was located 56ns (28 RF buckets) behind the main bunch and the time between the trailing bunch and precursor bunch was measured. This measurement uses a beam position monitor (BPM) pickup, which gives a signal approximately proportional to the derivative of the (nearly Gaussian) bunch's longitudinal profile. The time delay was measured from the zero crossing at the center of the BPM signal for the precursor and trailing bunches and this gave the time delay between the two bunches. This measurement was made with an HP54129A sampling scope. While the time delay was measured, the bunch distribution of the trailing bunch is measured with the streak camera by taking approximately ten streak camera images.

(II) The measurement is then repeated when another trailing bunch is injected, this time 42ns behind the main bunch. The trailing bunch at 56ns behind the main bunch is not dumped because the long-range wake potential at the storage ring's period ($t = 2.5\mu sec$) is negligible and its effect may be ignored. The time between the precursor bunch and trailing bunch is measured as well as the bunch length of the trailing bunch. This sequence is repeated with the timing delay between the main bunch and the precursor bunch of 28, 14, 12, 10, 8, 6, 4, and 2ns.

(III) All the bunches in CESR were dumped and the sequence in (I) and (II) were repeated with a current of 20mA in the main bunch.

The CESR machine parameters needed for the calculations are listed in table I.

RF frequency ω_{rf}	$3.1401x10^9 sec^{-1}$
RF voltage V_{rf}	6.91MV
Synchrotron radiation energy loss U_0	1.02MV/turn
Synchronous phase φ_0	81.5 degrees
CESR radius R	122.299m
CESR energy E_0	5.289GeV

TABLE I. The CESR machine parameters during the measurement.

Measurements of the CESR longitudinal bunch distribution were made with a 500-femtosecond-resolution Hamamatsu streak camera. A description of the camera and experimental set-up is described in detail in reference [4]. The data analysis techniques are described in detail elsewhere [4] but a brief discussion will be provided here.

To determine the bunch length from the streak camera's longitudinal profiles, the measured beam distributions are fitted to an asymmetric Gaussian function with a constant background given by

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

where I_0=pedestal, I_1=peak of the asymmetric Gaussian. The term $\mathrm{sgn}(z-\bar{z})A$ is the asymmetry factor that parameterized the shape of the asymmetric Gaussian. The longitudinal profile of the beam distribution in CESR is χ^2 minimized using the minimization package Minuit [5]. A χ^2 minimization was performed on each streak camera picture

$$\chi^2 = \sum_i^n \frac{[I(z_i; A, I_0, I_1, \bar{z}, \sigma) - x_i]^2}{x_i}$$

where x_i is the digitized signal from the streak camera profile. The fit will return the mean $\bar{z}$, asymmetry factor A, background level I_0, peak of the asymmetric Gaussian I_1, and width σ of the distribution. Figure 2 is an example of a streak camera profile fit to the asymmetric Gaussian distribution. The pertinent information retrieved from the asymmetric Gaussian distribution is the rms width

$$\sigma_z = \text{rms width} = \left\langle \left(z - \langle z \rangle\right)^2 \right\rangle^{1/2} = \left[1 + \left(3 - \frac{8}{\pi}\right)A^2\right]^{1/2} \sigma,$$

the mean of the distribution

$$\langle z \rangle = \text{mean} = \bar{z} + 2\sqrt{\frac{2}{\pi}} A\sigma$$

and the asymmetry factor A. These are the reported quantities from the measurements.

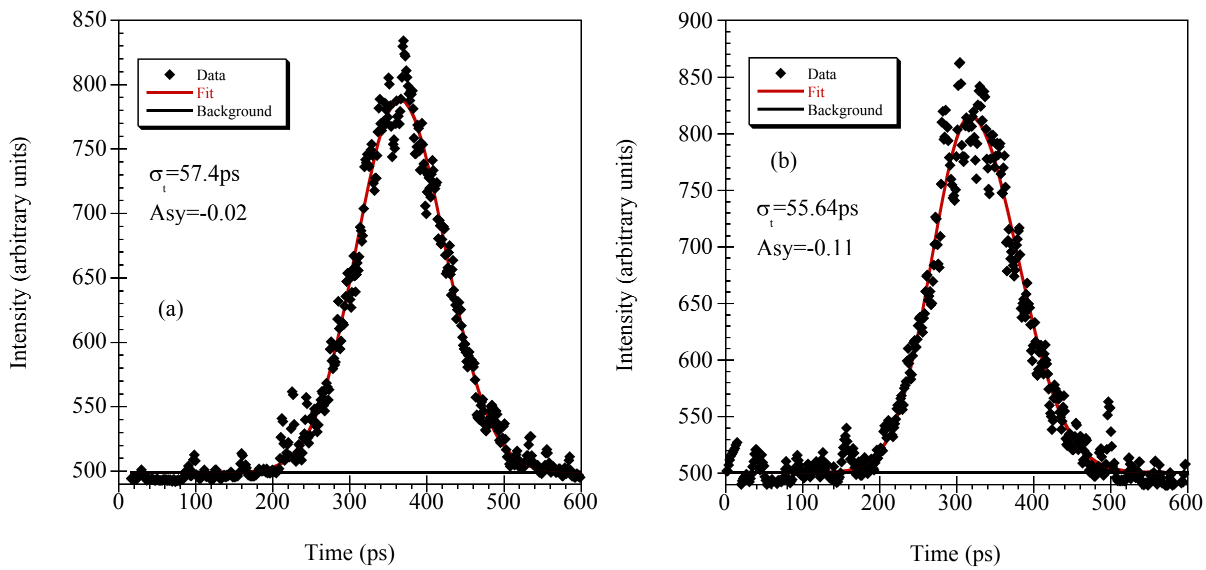

FIG. 2 (color). Two sample longitudinal profiles of the trailing bunch distribution measured by the streak camera. The current of the main bunch for both profile is 20mA and the time spacing between the main and trailing bunch is (a) 56ns (28 RF buckets) and (b) 2ns (one RF bucket).

The bunch length of the trailing bunch was measured using the streak camera for all the timing configurations and the two main bunch currents. The streak camera images were fit to an asymmetric Gaussian distribution and the mean bunch length and mean asymmetry value from the measurement is plotted in figs. 3 and 4.

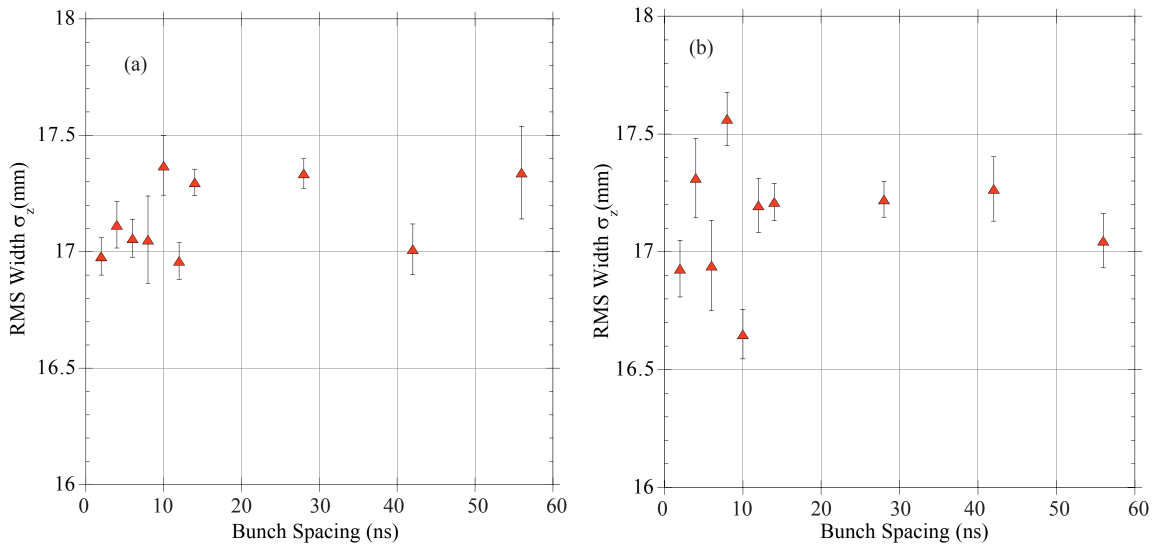

FIG. 3 (color). The test bunch length as a function of bunch spacing between the main bunch and the test bunch when the current in the main bunch was (a) 5mA and (b) 20mA.

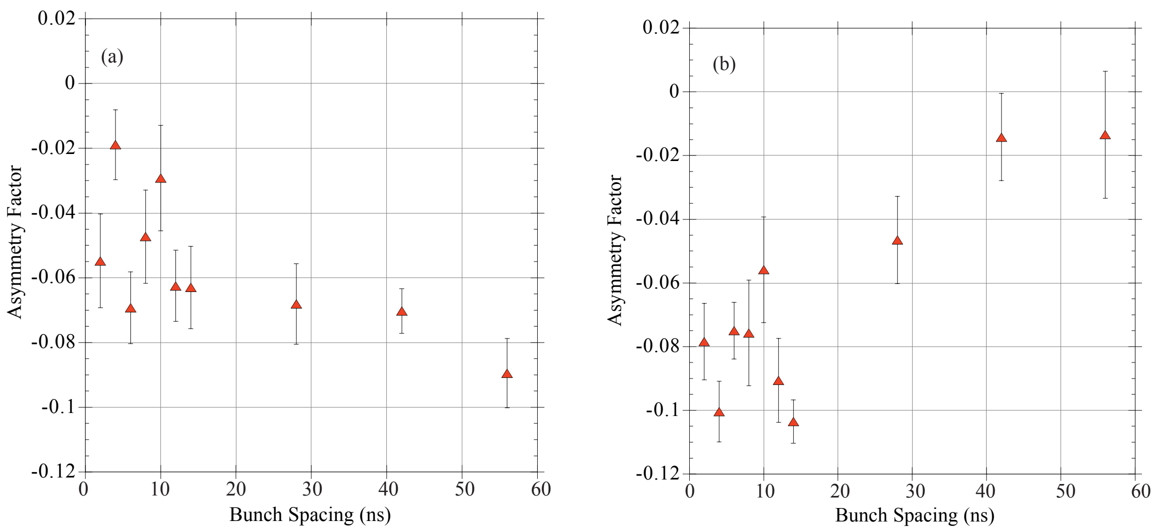

FIG. 4 (color). The test bunch asymmetry factor as a function of bunch spacing between the main bunch and the test bunch when the current in the main bunch was (a) 5mA and (b) 20mA.

The longitudinal wake potential is calculated using the data in table I and the equation

$$V_{wake} = \omega_{rf}\delta t V \sin\varphi_o - V_b$$

where δt is given by the expression

$$\delta t = (t_t(20mA) - t_t(5mA)) - (t_p(20mA) - t_p(5mA))$$

where t_t is the trailing bunch time at the given current and t_p is the precursor time at the given current. The beam loading voltage, V_b, is given by the expression

$$V_b = \frac{1}{2}\omega_{rf} q \left(\frac{R}{Q}\right) n_{cell} \exp\left(\frac{-\omega_{rf}^2 \sigma_z^2}{2c^2}\right)$$

where $\left(\frac{R}{Q}\right)$ is the CESR cavity shunt impedance, σ_z is the CESR bunch length. The wake potential is calculated at each data point and is plotted in fig. 5. The slope of the wake potential is also calculated at each data point from the expression

$$\Delta\dot{V}_{Wake} = -2\overline{\dot{V}}_{Wake} \frac{\Delta\sigma_\tau}{\overline{\sigma}_\tau}$$

where a positive slope points up and a negative slope points down.

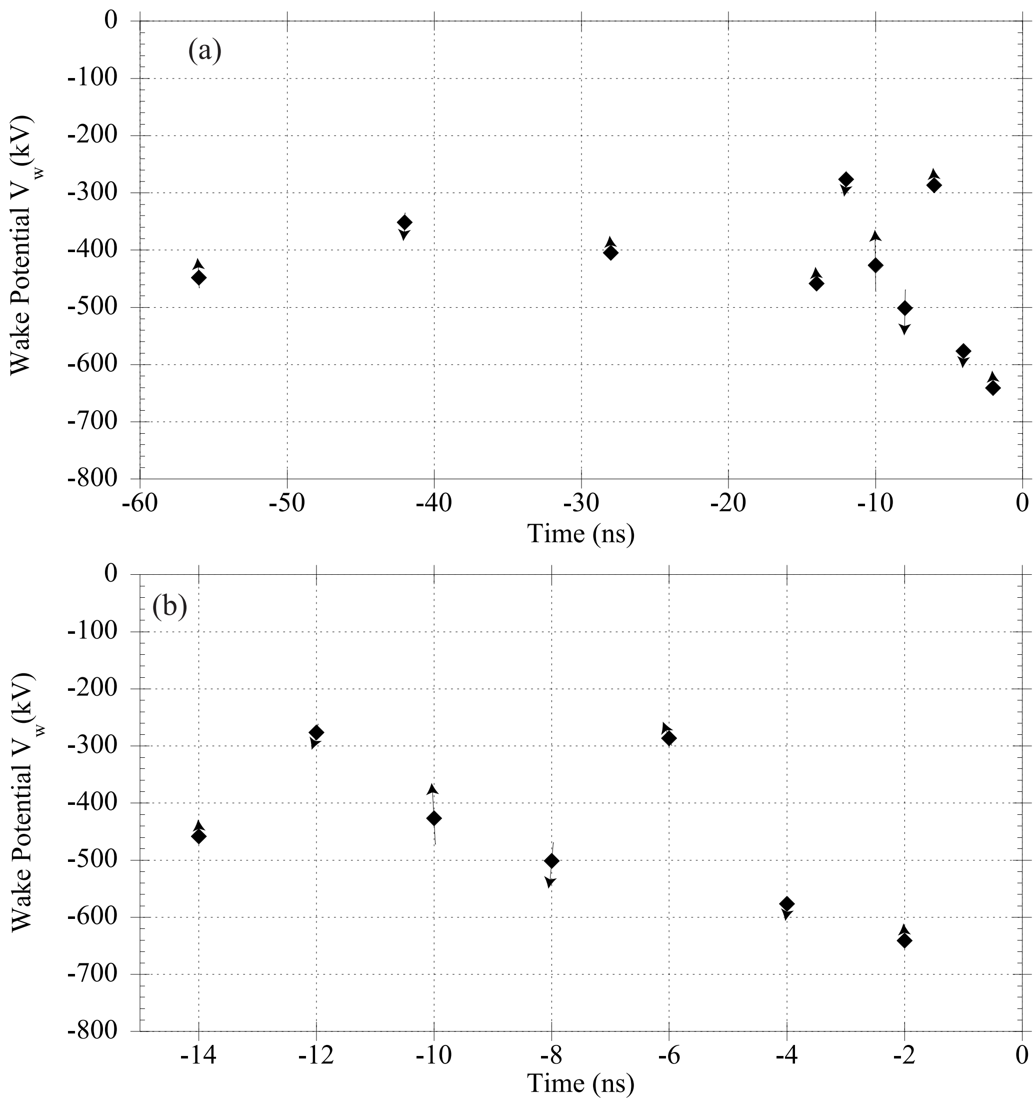

FIG. 5. The longitudinal wake potential behind a 15mA bunch in CESR for a (a) long time scale or a (b) short time scale. The arrows on the data points contain the slope of the wake potential at that time.

4. Conclusions

Several interesting features from the measurement should be pointed out:

1) The trailing bunch asymmetry factor changes as a function of current. Figure 4(a) and (b) point out that when the main bunch is at high current (20mA), the trailing bunch asymmetry factor is larger, especially when the trailing bunch is close (≤14ns) to the main bunch.

2) The trailing bunch length changes as a function of current. Figure 3(a) exhibits that at low main bunch current (5mA) the bunch length as a function of delay time from the main bunch is fairly constant at approximately 17.4mm. At high main bunch current (20mA) the bunch length is fairly constant when the time delay between the main bunch and trailing bunch is 12ns or greater, but when the time delay is less the 12ns there is a dramatic change in bunch length as a function of delay time.

3) The random error in the longitudinal wake potential is quantified by computing the spread in the times measured and computing the error in the wake potential associated with the spread in the time delay. The random errors determined in the measurement due to time differences gives the error bars on the wake potential plotted in fig. 6.

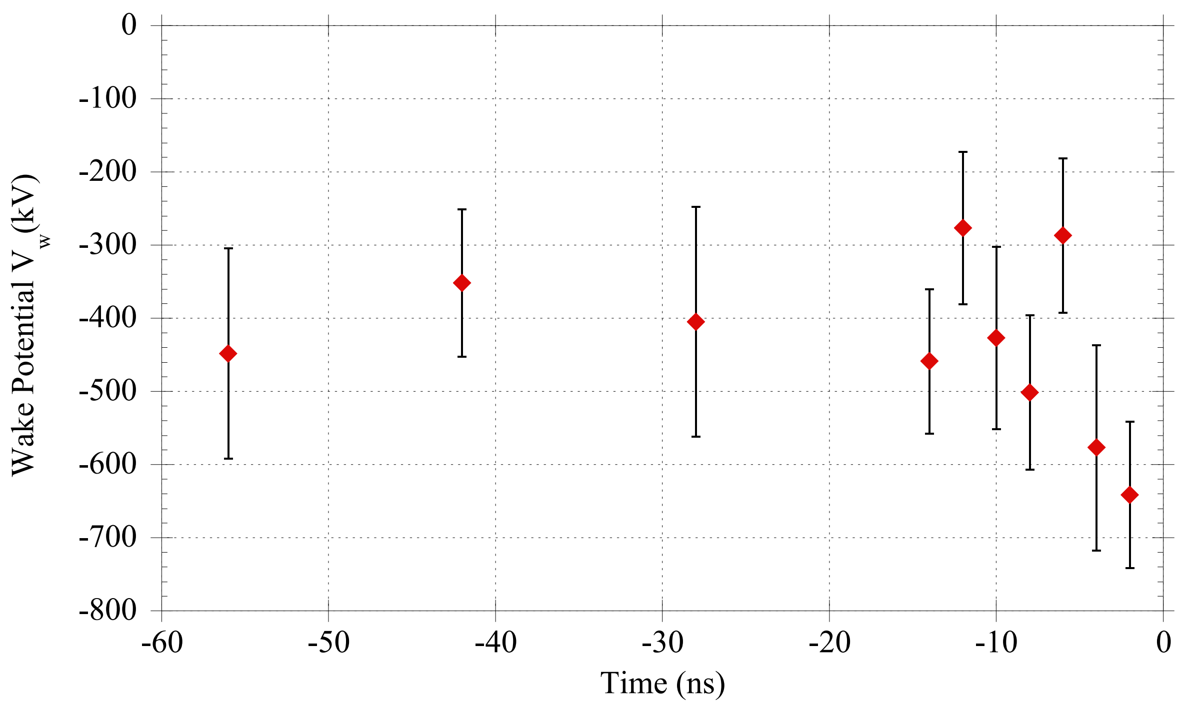

FIG. 6. The longitudinal wake potential as a function of time behind a 15mA bunch in CESR. The error bars on the data are the random errors associated with the measurement.

4) The bunch spacings chosen are useful in terms those used for high-energy physics collisions. For high energy physics collisions the bunches are conveniently at least 14ns apart so the wake potential was measured in 14ns intervals. The measurements between 2 and 12ns were made to give an idea of how the potential changes shortly after creation.
5) The slope of the wake potential can be inferred from the variation in bunch length as a function of time from the main bunch.

5. Acknowledgments

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6. References

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