Measurement of femtosecond electron bunches using a rf zero-phasing method

D. X. Wang, G. A. Krafft, and C. K. Sinclair
Thomas Jefferson National Accelerator Facility, 12000 Jefferson Avenue, Newport News, Virginia 23606
(Received 12 September 1997)

Bunch lengths as short as 84 fs (rms) have been measured at Jefferson Laboratory using a rf zero-phasing technique. To the best of our knowledge, this is the first accurate measurement of the longitudinal distribution function in this regime. In this paper, an analytical approach for computing the longitudinal distribution function and bunch length is described for arbitrary longitudinal and transverse distributions for the case where the intrinsic energy spread of the bunch is small compared to the correlated energy spread imparted by zero-phasing cavities. The measurement results are presented, which are in excellent agreement with numerical simulations. [S1063-651X(98)05802-4]

PACS number(s): 29.27.Fh, 29.17.+w, 41.75.Ht

I. INTRODUCTION

In recent years, there has been increasing interest in the use of very short electron bunches in short-wavelength free-electron lasers (FELs), linear colliders, advanced accelerators such as laser or plasma wakefield accelerators, and Compton backscattering x-ray sources [1–3]. Bunch length measurement is essential to develop such machines and also plays a critical role in developing and verifying new longitudinal measurement techniques such as coherent radiation methods [4].

The conventional technique of measuring short bunches using a streak camera cannot resolve bunch lengths of 100 fs or less [5]. Recently developed frequency-domain techniques which involve measurements of coherent radiation spectra lead to results that are not uniquely determined when the longitudinal distribution shape is not known *a priori* [4,6–8]. Therefore results from previously published measurements using these techniques are somewhat uncertain [8]. As a time-domain alternative, the zero-phasing technique has been used to measure longitudinal profiles and bunch lengths of picosecond bunches for many years. Good consistency was found between measurement and simulations [9–13]. However, the longitudinal profiles reported in Refs. [9, 11] were obtained in conditions where the transverse beam sizes can be neglected, while the formula used in Ref. [10] to calculate bunch lengths is only valid for Gaussian distributions. Furthermore, it is not clear if this technique can be applied to the femtosecond regime. In this paper, analytical formulas are given for computing the longitudinal distribution function and bunch length for arbitrary longitudinal and transverse distributions for cases such that the intrinsic energy spread of the bunch is small compared to the correlated energy spread imparted by zero-phasing cavities. The applicability of the technique to femtosecond bunches is demonstrated and confirmed by numerical simulations.

Because the zero-phasing technique has been successfully applied to analyze short bunches, and given the uncertainties inherent in the frequency-domain approach, it is asserted that such zero-phasing measurements are best able to provide a measurement standard in the subpicosecond regime, especially for measuring the beam longitudinal distribution function. Usually accelerating cavities and regions of nonzero dispersion are available at linear accelerators to allow such measurements to be completed. Because, in practice, the zero-phasing method is destructive and relatively time consuming, one can imagine calibrating more rapid nondestructive devices for monitoring purposes, and such uses are ideal applications of the frequency-domain techniques.

II. ANALYSIS OF ZERO-PHASING TECHNIQUE

Zero-phasing measurements utilize several rf accelerating cavities (zero-phasing cavities), a spectrometer, and a horizontal profile measuring device. The rf cavities operate at the zero crossing of the accelerating wave and impart a time-correlated momentum deviation along the beam bunch. Then a spectrometer translates the longitudinal momentum spread into a horizontal position spread. Based on measurement of the horizontal profile, the bunch length and longitudinal distribution function can be determined. In the analysis, it is assumed that the longitudinal phase space can be treated as an ellipse, and that the intrinsic energy spread or the width of the energy spread can be neglected at a given longitudinal position. In other words, only the linear tilt of the longitudinal ellipse is taken into account. Under this approximation, an analytical expression for the longitudinal distribution function is derived as a function of the horizontal distribution function and horizontal profile measured at the spectrometer with the zero-phasing cavities on.

The horizontal position of an electron at the spectrometer can be divided into two parts, i.e., a nondispersive term and a dispersive term, which are written as

$$x = x_0 + X = x_0 + \eta \frac{\delta E}{E_0} = x_0 + Cz, \tag{1}$$

where

$$C = C_0 + C_1 = (2\pi e V_{\rm rf}/\lambda_{\rm rf} + dE/dz)\,\eta/E_0, \tag{2}$$

η is dispersion of the spectrometer, E_0 and δE are average beam energy and energy deviation, respectively, z is longitudinal position at entrance of the zero-phasing cavities, $\lambda_{\rm rf}$ is the rf wavelength, $V_{\rm rf}$ is the summed accelerating voltage of the zero-phasing cavities, and dE/dz is the slope of the longitudinal phase-space ellipse. The linear slope of the accelerating voltage of the zero-phasing cavities, i.e., $2\pi eV_{\rm rf}/\lambda_{\rm rf}$, is used because the rf wavelength is much longer than the bunch length. All electrons with different combinations of x_0 and z that satisfy the condition given by Eq. (1) appear at the same horizontal position x at the spectrometer. The total number of electrons at x is the integral

$$F(x)=\int f_{x0}(x-Cz)f_z(z)dz, \tag{3}$$

where $F(x)$ is the horizontal profile measured at the spectrometer with the zero-phasing cavities on, $f_{x0}(x_0)$ is the transverse distribution function with no dispersion effect at the spectrometer, and $f_z(z)$ is the longitudinal distribution function at the entrance of the zero-phasing cavities. Therefore the measured horizontal profile is simply a convolution of the longitudinal distribution function and the horizontal nondispersive distribution function. The longitudinal distribution function can be deconvolved as

$$f_z(z=X/C)=\frac{C}{2\pi}\int\left[\frac{\int F(x)e^{ikx}dx}{\int f_{x0}(x)e^{ikx}dx}\right]e^{-iCzk}dk$$
$$\approx\frac{C}{2\pi}\int\left[\frac{\int F(x)e^{ikx}dx}{\int f_{x}(x)e^{ikx}dx}\right]e^{-iXk}dk. \tag{4}$$

In principle, $f_{x0}(x)$ may be directly measured with an experimental arrangement where the profile measurement device is placed in a straight beam line at the same distance from the spectrometer dipole and with the same optical properties as the spectrometer, but with no dispersion. However, in practice, $f_x(x)$ may be approximated by the horizontal profile measured at the spectrometer with the zero-phasing cavities off, if the dispersive part of the initial energy spread is small compared to the horizontal beam size. Such an approximation was made for the measurement, even though the estimated dispersive part is only about a factor of 2 smaller than the nondispersive part in the worst case with the zero-phasing cavities off, and the resulting error is only about 5% or 4 fs for the shortest bunch case. If $F(x)$ and $f_{x0}(x)$ are both Gaussian distributions, the longitudinal distribution function $f_z(z)$ is also Gaussian. From Eq. (4), a relation between longitudinal bunch length and measured transverse bunch widths is found to be

$$\sigma_z=(\Omega^2-\sigma_x^2)^{1/2}/C, \tag{5}$$

where σ_z, Ω, and σ_x are corresponding widths of the Gaussian profiles, as used in Ref. [10]. As another example, if the width of $f_x(x)$ is negligibly small compared to that of $F(x)$, it can be replaced by a δ function, and the longitudinal distribution function equals the measured profile, i.e., $f_z(z=X/C)=CF(X)$ as in Refs. [9, 11], with a scale conversion factor C between the horizontal and longitudinal dimensions. More generally, Eq. (4) should be used in situations, as in linacs, where the distributions are not Gaussian or, as is necessarily the case when short bunches are measured, where the initial transverse beam size is not negligible.

$f_z(X)$ can be readily computed using Eq. (4), if $F(x)$ and $f_{x0}(x)$ or $f_x(x)$ are measured. By applying the scale factor of C, $f_z(z)$ is obtained. However, usually, C_0 can be experimentally determined but dE/dz is unknown *a priori*. To overcome this problem, the horizontal profiles are measured at both zero-crossing points of the rf waves, 180° apart, which alters the sign of C_0. When C_0 and C_1 have the same sign, the measured linear energy spread is larger than that imparted by zero-phasing cavities, resulting in a wider $F(x)$. The rms values of $X^+_{\rm rms}$ and $X^-_{\rm rms}$ can be calculated from corresponding $f_z^{\pm}(X)$ functions, where + and − signs represent +90° and −90° rf phases from the crest. The rms value of $z_{\rm rms}$ is given by

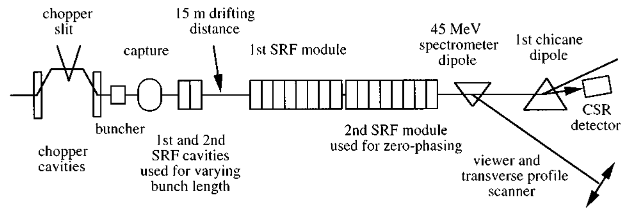

FIG. 1. Schematic block diagram of CEBAF injector layout.

$$z_{\rm rms}=\frac{X^+_{\rm rms}}{|C_0|+|C_1|}=\frac{X^-_{\rm rms}}{|C_0|-|C_1|}. \tag{6}$$

Notice that all rms values are positive and $|C_0|$ is usually much larger than $|C_1|$. The longitudinal rms bunch length is given by

$$z_{\rm rms}=\frac{X^+_{\rm rms}+X^-_{\rm rms}}{2|C_0|}, \tag{7}$$

and the initial phase-space slope normalized by the rf slope is given by

$$|C_1|/|C_0|=|(dE/dz)|/|(2\pi eV_{\rm rf}/\lambda_{\rm rf})|=\frac{X^+_{\rm rms}-X^-_{\rm rms}}{X^+_{\rm rms}+X^-_{\rm rms}}. \tag{8}$$

The sign of the initial phase-space slope is easily determined from the sign convention of the rf wave. The longitudinal distribution function $f_z(z)$ is obtained using scale factors given by Eq. (6), accordingly. In principle, the distribution functions derived from both cases should be identical. In practice, there will be differences resulting from deviations of the original longitudinal phase-space distribution from the ideal one. Such differences can be used to evaluate the error of the measurements.

The formula and measurement procedure were tested using PARMELA computer simulations. This code has been used extensively during commissioning of Jefferson Laboratory's CEBAF (continuous electron beam accelerator facility) to verify experimental results. Very good agreement has been found between various measurements and simulation results in the past. The zero-phasing measurement was performed numerically and compared to the simulated bunch length. The test cases showed good agreement over bunch lengths in the range of 100 to 400 fs, with a 10 fs systematic offset, indicating that the assumptions are good.

III. EXPERIMENTAL RESULTS

The measurement was carried out at the CEBAF injector. A block diagram of the injector layout is given in Fig. 1. A 100 keV cw electron beam is generated and chopped by a

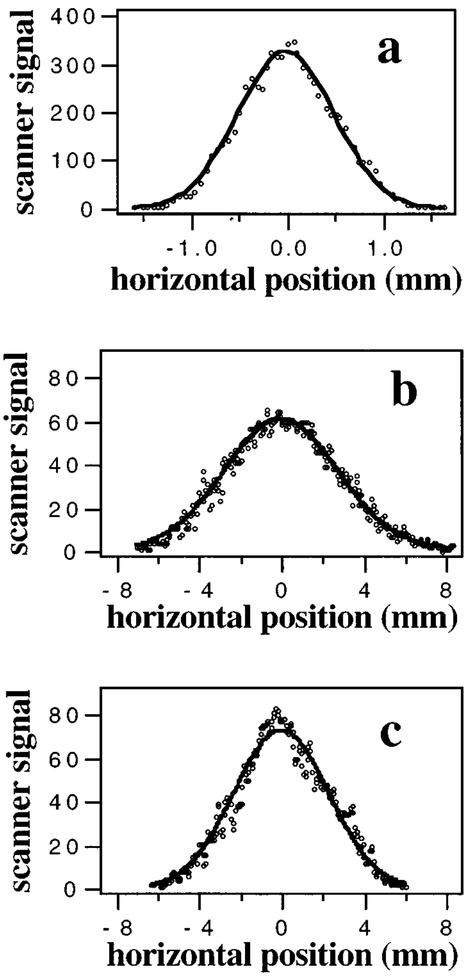

FIG. 2. Horizontal profile measured by the wire scanner at the spectrometer, where the scanner signal is proportional to the charge density and the circles are from measurement and the solid curves are Gaussian fittings. Profile (a) was measured with the zero-phasing cavities off while profiles (b) and (c) were measured with the zero-phasing cavities at $+90°$ and $-90°$ off the crest.

pair of rf chopper cavities into a bunch train with variable duration from 0 to 40 ps (rms) separated by 2 ns. The beam is bunched by a rf buncher and accelerated to 500 keV by a rf ''capture'' cavity, a five-cell variable β normal rf accelerating structure. Then the beam is further bunched and accelerated to 5 MeV by the two superconducting rf (Srf) cavities. Following acceleration to the final injection energy of 45 MeV by 16 Srf cavities, little additional bunching occurs, due to longitudinal relativistic effects. Nominally, 16 Srf cavities in the first and second Srf modules run on crest to achieve maximum energy gain and minimum energy spread. During the measurement of the shortest bunches, the last eight Srf cavities are phased to plus and minus 90° off crest. A wire scanner is used to measure horizontal profile at the spectrometer. Three typical profiles are shown in Fig. 2 and can be fit closely to Gaussian distributions. Both zero phases of each individual zero-phasing cavity are determined by finding the phase that yields zero transverse movement at the spectrometer viewer when the cavity is turned on and off. The beam energy and summation of the zero-phasing cavity gradient were measured by the spectrometer Hall probe. The experimental parameters in this measurement are $\lambda_{\rm rf}$ of 20

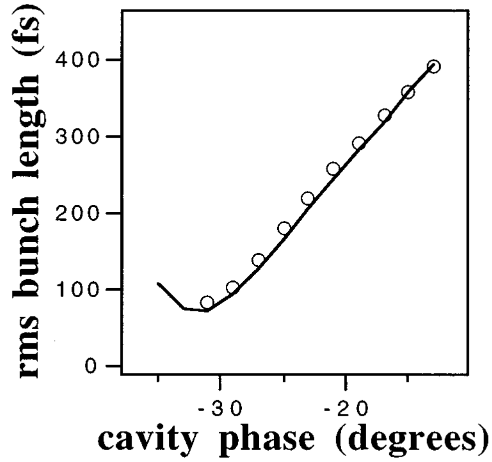

FIG. 3. The bunch length versus the second Srf cavity phase, where the circles are from measurement and the solid curve is from simulation.

cm, η of 1.52 m, $V_{\rm rf}$ of about 20 MV, E_0 of about 25 MeV, and 3×10^5 electrons per bunch. Other estimated beam parameters are rms intrinsic energy spread of 20 eV, rms normalized longitudinal emittance of 0.3 π ps keV, rms normalized transverse emittance of 0.14 π mm mrad, and rms horizontal and vertical beam size of 0.25 and 0.5 mm at the zero-phasing cavity, respectively. It is noticed that the bunch length at the spectrometer viewer is usually significantly longer than the bunch length at the zero-phasing cavity, due to the dispersion of the dipole. Collective space-charge effects are negligibly small due to the low charge per bunch and the high energy. Higher-order horizontal focusing terms due to energy deviations are estimated from optics to be three orders of magnitude smaller than the dispersion term.

The bunch length was systematically changed by varying the second Srf cavity phase, resulting in a serial longitudinal phase space rotation. Excellent agreement has been achieved between the measurement and simulation, shown in Fig. 3. In addition, the measurement results are consistent with a power measurement of the coherent synchrotron radiation (CSR). As expected, CSR power increased when the bunch length became shorter, and minimum bunch length yielded maximum CSR power [14]. In Fig. 4, the left side of Eq. (8) is plotted from simulation in the solid line while the right side is displayed from measurement in the circles, as the phase of the second Srf bunching cavity is varied as in Fig. 3. Measurements and simulation results agree well. It is noted that the zero value point represents the upright position of the ellipse in the longitudinal phase space, where the shortest bunch was obtained in both experiment and simulation, i.e., the minimum point in Fig. 3. There is a steep slope around the zero point where the slope of the ellipse changes sign, corresponding to the transition from undercompression to overcompression. Therefore the maximum slope of the ellipse dE/dz is about a factor of 7 smaller than the rf slope, $2\pi\, eV_{\rm rf}/\lambda_{\rm rf}$ of 720 MeV/m. The resolution about 30 fs (rms) for this particular measurement setup is limited by the transverse beam size. It should be stressed that the bunch distribution and length obtained by this measurement are the ones at the zero-phasing cavities, not at the transverse profile measuring location.

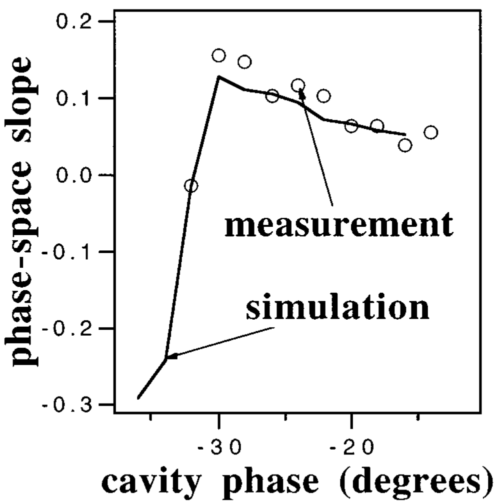

FIG. 4. The normalized longitudinal phase-space slopes. The circles are the measurement of the right-hand side of Eq. (8), $(X^+_{\rm rms}-X^-_{\rm rms})/(X^+_{\rm rms}+X^-_{\rm rms})$, while the solid curve is the left-hand side, $(dE/dz)/(2\pi eV_{\rm rf}/\lambda_{\rm rf})$, from simulation.

IV. CONCLUSION

The zero-phasing technique provides a means of measuring the longitudinal density distribution function and the bunch length of fs bunches. It has played a crucial role at CEBAF in characterizing the bunching process and calibrating a noninvasive CSR bunch length monitor that is an invaluable tool for machine operations. Measurement at both zero crossings and the above analysis not only provide a means of unambiguously determining the longitudinal distribution and bunch length, but also give additional information about the longitudinal phase-space orientation that is very valuable in studying the bunching-forming process and comparing it to the simulation model. In addition, it was also possible to check how close the assumptions were to reality. Similarly to a streak camera, a bunch-to-bunch resolution may be obtained by using a vertical rf sweeper after the spectrometer dipole plus a gated camera.

An electron bunch length as short as 84 fs (rms) has been measured using the zero-phasing technique. Analytical formulas are derived for calculating the longitudinal distribution function and bunch length and for determining the longitudinal phase-space orientation, at least, in an average sense. To the best of our knowledge, this is the first accurate measurement of the beam longitudinal distribution in the regime of less than 100 fs, and zero phasing is the only technique that has demonstrated such a capability. Numerical simulation provides validation of the assumptions of the technique. The systematic measurement results are in excellent agreement with the simulation and consistent with CSR power measurements.

ACKNOWLEDGMENTS

The authors would like to thank B. Dunham and H. Liu for help running the PARMELA simulation code and CEBAF operations personnel for help with the measurements. This work was supported by the U.S. Department of Energy under Contract No. DE-AC05-84ER40150.

[1] H. Winick, K. Bane, R. Boyce, J. Cobb, G. Loew, P. Morton, H. D. Nuhn, J. Paterson, P. Pianetta, T. Raubenheimer, J. Seeman, R. Tatchyn, V. Vylet, C. Pellegrini, J. Rosenzweig, G. Travish, D. Prosnitz, E. T. Scharlemann, K. Halbach, K. J. Kim, R. Schlueter, M. Xie, R. Bonifacio, L. De Salvo, and P. Pierini, Nucl. Instrum. Methods Phys. Res. A **347**, 199 (1994).

[2] R. H. Siemann, *Proceedings of the 1993 Particle Accelerator Conference, Washington, D.C., May 1993*, edited by S. T. Corneliussen (IEEE, New York, 1994) (IEEE Cat. No. 93CH3279-7).

[3] W. B. Mori and T. Katsouleas, in *Advanced Accelerator Concepts*, edited by P. Schoessow, AIP Conf. Proc. No. 335 (AIP, New York, 1995), p. 112.

[4] D. X. Wang (unpublished).

[5] A. Lumpkin, in *Micro Bunches Workshop*, AIP Conf. Proc. No. 367, edited by E. B. Blum, M. Dienes, and J. B. Murphy (AIP, New York, 1995), p. 327.

[6] K. Ishi, Y. Shibata, T. Takahashi, H. Mishiro, T. Ohsaka, and M. Ikezawa, Phys. Rev. A **43**, 5597 (1991).

[7] R. Lai and A. J. Sievers, Phys. Rev. E **52**, 4576 (1995).

[8] H. Lihn, P. Kung, C. Settakorn, and H. Wiedemann, Phys. Rev. E **53**, 6413 (1996).

[9] L. Rivkin, K. Bane, P. Chen, W. Gabella, T. Higo, A. Hofmann, W. Linebarger, S. Kheifets, T. Knight, P. Morton, J. Paterson, T. Raubenheimer, R. Ruth, J. Spencer, R. Stege, J. Sheppard, W. Spence, and P. Wilson, in *Proceedings of the First European Particle Accelerator Conference, Rome, June 1988*, edited by Sergio Tazzari (World Scientific, Singapore, 1989), p. 634.

[10] J. Seeman, in *Proceedings of the 1988 Linear Accelerator Conference, Williamsburg, VA, October 1988* (Continuous Electron Beam Accelerator Facility, Springfield, VA, 1989), p. 441.

[11] K. Bane, SLAC Report No. SLAC-PUB-5177, 1990 (unpublished).

[12] K. Bane, C. Adolphsen, T. L. Lavine, M. Ross, J. Seeman, and K. Thompson, in *EPAC90: Proceedings of the Second European Particle Accelerator Conference, Nice, June 1990*, edited by P. Martin and P. Mandrillon (Editions Frontieres, Gif-sur-Yvette, 1991), p. 1762.

[13] K. Bane, SLAC Report No. SLAC/AP-80, 1990 (unpublished).

[14] D. X. Wang, G. A. Krafft, E. Price, P. A. D. Wood, D. W. Porterfield, and T. W. Crowe, Appl. Phys. Lett. **70**, 529 (1997).