A Field-Based Technique for the Longitudinal Profiling of Ultrarelativistic Electron or Positron Bunches Down to Lengths of ≤ 10 Microns*

R. Tatchyn
Stanford Linear Accelerator Center, Stanford, CA 94305, USA

Abstract

Present and future generations of particle accelerating and storage machines are expected to develop ever-decreasing electron/positron bunch lengths, down to 100 μ and beyond. In this paper a method for measuring the longitudinal profiles of ultrashort ($1000\,\mu \sim 10\,\mu$) bunches, based on: 1) the extreme field compaction attained by ultrarelativistic particles, and 2) the reduction of the group velocity of a visible light pulse in a suitably-chosen dielectric medium, is outlined.

I. INTRODUCTION

A number of widely known techniques for measuring the longitudinal density profiles of single-pass or recirculating particle bunches are employed on present-day particle accelerators and storage rings. Two basic approaches to this problem can be noted. The first involves passing the beam through axially distributed inductive or capacitive pick-up sensors [1,2,3]. In temporal-length regimes where the bandpass characteristics of the detectors and signal-processing electronics are sufficiently wide, Fourier analysis of the detector's spectral response can be used to resolve features of the bunch profile. The second involves: 1) passing the spontaneous radiation emitted by the particles in a bunch onto a streak camera [4] or fast photodiode [5,6], and 2) unfolding the longitudinal distribution from the streak camera or oscilloscope sweeps. Although techniques based on these approaches have generally kept pace with the measurement tasks dictated by evolving bunch parameters, the emerging introduction of advanced storage rings and linacs with emittances and longitudinal beam sizes [7,8,9] of 1-2 orders of magnitude smaller than those realized today can be expected to eventually start exceeding the capabilities of conventional methods of characterization.

In this paper a method with the capability of accurately characterizing the longitudinal profiles of charged-particle bunches down to lengths of 10 μ and beyond is outlined [10,11]. It is based on essentially three conventional precepts: 1) the availability of high power visible/UV laser pulses with temporal lengths of 10fs or less; 2) the high compaction of an ultrarelativistic particle's transverse electric and magnetic fields; and 3) the modulation of a dielectric material's index of refraction by the combined fields of the laser and electron bunch fields. The following definitions will be employed:

E[GeV] ≡ average energy of a charged-particle beam
I[mA] ≡ average current associated with a particle beam
q ≡ magnitude of the CGS unit of charge
c[cm/s] ≡ speed of light
m_e[g]c^2 ≡ electron (positron) rest energy in ergs
m_p[g]c^2 ≡ proton (antiproton) rest energy in ergs
βc ≡ speed of a relativistic particle
$\gamma \equiv \sqrt{1-\beta^2}$ ≡ relativistic contraction factor
$\rho(z)$[#/cm] ≡ number density of a particle bunch vs. z
N_C ≡ total number of particles in a bunch
$g(z) = \rho(z)/N_C$ ≡ (normalized) Gaussian particle density
$\sigma_x, \sigma_y, \sigma_z$ ≡ standard deviations of random distributions of particle positions vs. x, y, and z directions
N_B ≡ total number of bunches in a storage ring

* Supported by DOE Offices of Basic Energy Sciences and High Energy and Nuclear Physics and Department of Energy Contract DE-AC03-76SF0015.

0-7803-1203-1/93$03.00©1993 IEEE

II. FIELD BASIS OF PROFILING METHOD

Consider a charged particle bunch with N_C particles traveling, on the average, along a locally rectilinear trajectory. Referring to Fig. 1, we take the axis of this trajectory

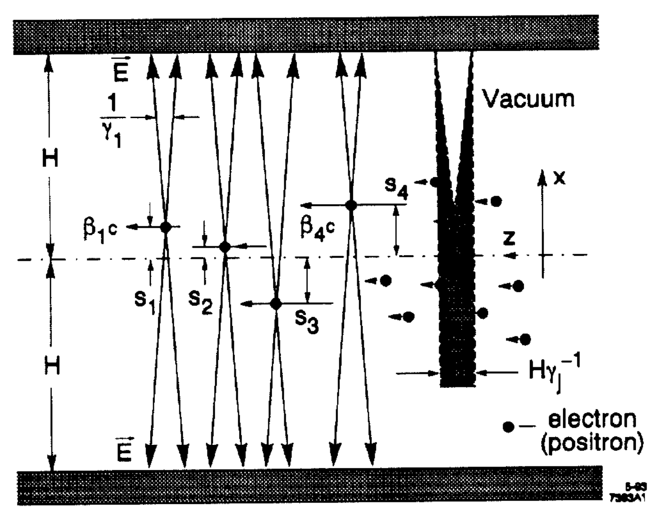

Figure 1. Parameters of particle bunch in vacuum.

to be coincident with the symmetry axis (z-axis) of a cylindrical (rectangular) duct of radius (half-width) H. For normally distributed particle positions, we associate the main bunch dimensions with the quantities $2\sigma_x, 2\sigma_y$, and $2\sigma_z$. For our present analysis we will take $\sigma_x, \sigma_y << H$. This restriction, valid whenever the maximum transverse radius of the bunch is much smaller than the duct diameter, allows the representation of the bunch by a filamentary distribution of charge. Of central importance is the instantaneous peak transverse field generated at the location (x=H,z) by an electron j located at point (s_j,s'_j,z), where s'_j is its displacement vs. y. Under the assumed restriction, the transverse field magnitude at H can be expressed as

$$\left|\vec{E}(x=H,z)\right|_e \left[\frac{KV}{cm}\right] = \frac{0.3\gamma_j q}{\left(H-s_j\right)^2+\left(s'_j\right)^2} \approx \frac{0.3\gamma_j q}{H^2}. \quad (1)$$

Corresponding to the relativistic enhancement of the transverse field strength is a corresponding attenuation of the forward component by the amount γ_j^{-2}. Assuming , then, that most of the electron's field is concentrated within the angle γ_j^{-1}, it follows that the limiting resolution of its instantaneous z-position at x=H is given by

$$\Delta z_e = H/\gamma_j. \quad (2)$$

An important quantity is the number of particles in the vicinity of electron j that also contribute significantly to the field at (x=H,z). Assuming a minimal energy spread, we can drop the index and define the designated group of electrons by projecting the resolution segment H/γ from the point (x=H,z) back toward the z axis. This yields

$$N_{1/\gamma}(z) = H\rho(z)/\gamma = \Delta z_e \rho(z). \quad (3)$$

For γ^{-1} sufficiently small, the magnitude of the total field at (x=H,z) is given approximately by

$$\left|\vec{E}(x=H,z)\right|[KV/cm] = N_{1/\gamma}\left|\vec{E}\right|_e \approx \frac{0.3q\rho(z)}{H}. \quad (4)$$

For the case of a Gaussian $\rho(z)$, designated by $N_C(g(z))$, the instantaneous transverse field profile can be re-expressed in terms of the total number of particles in the bunch by

$$\left|\vec{E}(x=H,z)\right|[KV/cm] \approx \frac{0.3N_C q g(z)}{H}. \quad (5)$$

A graph displaying practical parameter ranges and attainable field strengths from charged-particle bunches in linacs or storage rings is shown in Fig. 2. First, we note the high energy regime required for proton (antiproton) beams for the method to be considered useful. Second, in order to obtain significant field strengths, there must be a sufficient quantity of particles within one electronic resolution length (H/γ) along the beam. This quantity, which should ideally be present in the sparsest region of the bunch to be measured, can be used to establish the minimum current levels at which the profiling technique can be applied. In applying the graph, different storage rings (or linear machines) are identified not by their species of particle or energy (which is assumed to exceed a well-defined minimal value), but by their average currents and interbunch intervals. For example, taking the average current in the LCLS [9] to be approximately 0.15 μA, with an interbunch inteval of 10^7ns and a 150 μ full bunch

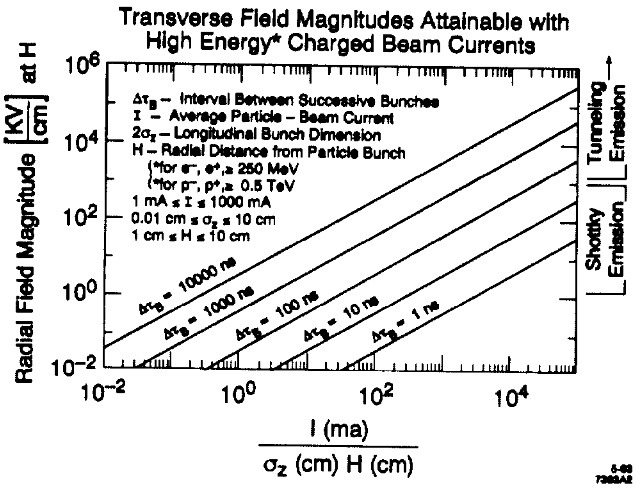

Figure 2. Field magnitudes obtainable from charged-particle bunches.

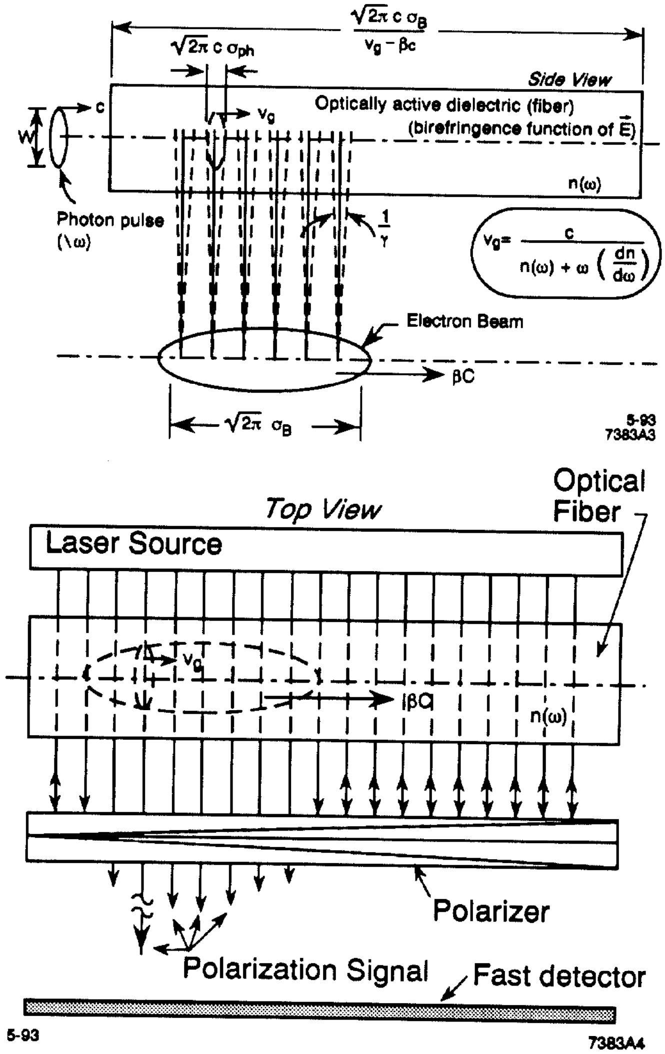

Figure 3. Parameters of a modulated-dielectric bunch profiler.

length, extrapolation of the curves in the graph indicates that field strengths in excess of 10^3kV/cm could be attained at distances of the order of 1cm from the bunch axis.

III. FIELD SCANNING AND DETECTION

As schematized in Fig. 3, the essential component of the profiling method is the interaction of a probe photon pulse of full length $(2\pi)^{1/2}\sigma_{ph}$ with the particle bunch field as they both traverse a suitable dielectric medium If we assume the group velocity, v_g, of the photon pulse to be different from βc, the particle bunch velocity, and $\sigma_{ph} << \sigma_B (= \sigma_z)$, it is evident that the photon pulse will "scan" the electron field profile in a time equal to the temporal length of the bunch dilated by the factor $1/\left(\beta - \left(v_g/c\right)\right)$. A necessary condition to be fulfilled is that the dispersion inside the dielectric be small enough for the photon pulse to retain its shape (viz., length) without excessive loss of intensity during the scan. The physical basis for detection lies in the non-linear modulation of the dielectric material by the combined fields of the photon and particle bunches. Light from a tertiary source, e.g., a laser, is then instantaneously perturbed by the modulated index of refraction, and the perturbation is recorded. In principle, variations of intensity, scattering direction, polarization, or dielectric-boundary effects could be effected [12]. To minimize convolution blurring, an apparent constraint is that the thickness of the dielectric (e.g., the diameter of an optical fiber) should ideally be of the same order of size as the required resolution length. Thus, both the (instantaneous) length and thickness of the interaction region could each need to be made as small as several microns. In this limit, it is evident that the modulated fraction of photons from the tertiary source within one resolution interval could become extremely small, making the choice of radiation parameters for modulation and detection critical to the applicability of the method. We note that although the absolute number of modulated photons could be increased by enlarging the dielectric in the azimuthal direction, their net fraction will remain the same, necessitating a similar scaling of the output power of the tertiary photon source. Denoting the full, dispersion-dependent dielectric constant by n' (i.e., n'=c/v_g), selected dimensional and physical parameters that would be required to configure a profiling system for a typical storage ring energy are calculated in Table 1.

TABLE 1.
Bunch profiling system parameters for 5.11 GeV

n'	σ_B [μ]	σ_{ph} [μ]	[fs]	Scan Time [ns]	Diel. Length [m]
1.001	3000	0.6	2	25	7.5
1.001	300	0.6	2	2.5	0.75
1.001	30	0.6	2	0.25	0.075
1.01	3000	0.6	2	2.5	0.75
1.01	300	0.6	2	0.25	0.075
1.01	30	0.6	2	0.025	0.0075

For the assumed indices of refraction, it is apparent that feasible dielectric lengths exist for which the tabulated laser pulse and particle bunch lengths are consistent. Further analytical studies are in progress to identify suitable dielectric materials and configurations with regard to n' and the magnitude and time scales of non-linear field effects.

IV. ACKNOWLEDGEMENTS

Useful discussions with Karl Bane and Roberto Coisson are acknowledged.

V. REFERENCES

[1] C.-R. Carman and J.-L. Pellegrin, "The Beam Positions of the SPEAR Storage Ring," Nucl. Instrum. Meth. 113, 423(1973).

[2] T. Katsura, Y. Kamiya, K. Haga, and T. Mitsuhashi, "A Beam Position Feedback System for Beam Lines at the Photon Factory," Proceedings of the 1987 IEEE Particle Accelerator Conference, IEEE Catalog No. 87CH2387-9, p. 538.

[3] R. Webber, J. Fritz, S. Holmes, W. Marsh, J. Zagel, "A Beam Position Monitor System for the Fermilab Booster," p. 541.

[4] R. Tatchyn, A. Toor, H. Kilic, J. Hares, J. Kilkenney, P. Csonka, H. Watanabe, A. Fuller, "On-axis streak camera measurements of undulator light on Beam Line V at SPEAR," SPIE Proceedings No. 733, 103(1987).

[5] I. Munro and A. Sabersky, "Synchrotron Radiation as a Modulated Source for Flourescence Lifetime Measurements and for Time-Resolved Spectroscopy," in Synchrotron Radiation Research, H. Winick and S. Doniach, eds., Plenum Press, New York, 1980, p. 323 ff.

[6] D. R. Kania, R. J. Bartlett, and P. Pianetta, "Subnanosecond time resolved measurements of synchrotron x-ray pulses using photoconductive detectors," Nucl. Instrum. Meth. A246, 534(1986).

[7] M. Cornacchia and H. Winick, eds., Proceedings of the Workshop on Fourth Generation Light Sources, SSRL, Feb. 24-27, 1992, SSRL Pub. 92/02.

[8] T. Raubenheimer, "The Preservation of Low Emittance Flat Beams," this conference - B2, 1993.

[9] J. Seeman, K. Bane, T. Raubenheimer, "Electron Transport of a Linac Coherent Light Source (LCLS) Using the SLAC Linac," this conference - Jb19, 1993.

[10] R. Tatchyn, "A Field-Based Longitudinal Profiling Scheme for Short Charged Particle Bunches in High Energy Storage Rings, " SSRL ACD-Note 119, February 24, 1992.

[11] R. Tatchyn, "Field-Based Longitudinal Profiling Schemes for Short Charged Particle Bunches in High Energy Storage Rings, " Proceedings of the Workshop on Fourth Generation Light Sources, M. Cornacchia and H. Winick, eds., SSRL, Feb. 24-27 1992, SSRL Pub. 92/02, p. 229.

[12] R. R. Alfano, ed., The Supercontinuum Laser Source, Springer-Verlag, New York, 1989.