ANALYSIS OF A SINGLE-SHOT LONGITUDINAL BUNCH PROFILING SYSTEM BASED ON AN ULTRA-SHORT PULSE Ti:SAPPHIRE LASER*

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Abstract

Recent advances in ultra-short pulse high-power laser technology include the generation of <10 fs pulses at 1 μ wavelengths in the multi-terawatt regime. These parameters, coupled with the high per-pulse energy of the new sources, make possible the consideration of longitudinal bunch profiling schemes capable of accurately registering the longitudinal bunch density in a single shot. In this paper we assess the performance and advantages of a longitudinal bunch profiling system based on multi-photon absorption and fluorescence stimulated by the combined bunch and laser fields in a gaseous medium.

1 INTRODUCTION

A number of diagnostic techniques for measuring the longitudinal density profiles of single-pass or recirculating particle bunches are employed on present-day particle accelerators and storage rings. Examples include: 1) electronic spectral analysis of the outputs of distributed inductive or capacitive pickups placed in proximity to the beam [1,2], 2) streak camera or fast photodiode sampling of the spontaneous radiation emitted by the particle bunch [3,4], and 3) Michelson (autocorrelation) interferometry applied to quasi-coherent transition or synchrotron radiation emitted by the bunch [5]. Potential drawbacks of 1) and 2) for very short bunches include the limited angular or spectral bandwidths of conventional electronic deflection systems and instrumentation. Another drawback is the relatively weak signal induced or emitted by the bunch in a single pass, which usually necessitates sampling a large number of pulses to obtain acceptable statistics. These drawbacks can be expected to limit, and in some cases obviate, the applicability of the cited techniques, especially as particle bunch lengths decrease down to below 100 μ, a trend exemplified by the bunch parameters of the Ångstrom-wavelength Linac Coherent Light Source (LCLS) [6]. Needless to say, a diagnostic tool with the capability of accurately profiling a particle bunch in a single pass would contribute greatly to our ability to study and control systems (such as the LCLS) whose performance is stringently determined by the longitudinal distribution of electrons.

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In this paper we describe an extension of a previously-proposed method [7,8] with the capability of accurately characterizing the longitudinal profiles, in a single shot, of high energy charged-particle bunches down to lengths of 10μ and beyond. It is based on the availability of IR/visible/UV terawatt laser pulses with temporal lengths of 10fs [9] or less and the following three principles: 1) the reduction in the group velocity of the laser pulse traveling through a gas; 2) the high compaction of an ultrarelativistic particle's transverse electric and magnetic fields; and 3) the nonlinear modulation of multiple-photon absorption in a gas by the combined laser and electron bunch fields. As will be seen, it is the shortness of the laser pulse in comparison to the bunch that enables it to be used as temporal probe, while the large amount of energy it contains is the key to generating a signal strong enough for reliable single-shot diagnostics.

2 REVIEW OF BASIC REQUIREMENTS

The following definitions are employed:

E[GeV]	≡	average energy of a charged-particle beam
I[mA]	≡	average current of a particle beam
q	≡	magnitude of the CGS unit of charge
me[g]c2	≡	electron (positron) rest energy in ergs
$m_p[g]c^2$	≡	proton (antiproton) rest energy in ergs
β_c	≡	speed of a relativistic particle
$\gamma = \sqrt{1-\beta^2}$	≡	relativistic contraction factor
ρ(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
N_B	≡	total number of bunches in a storage ring

Consider a charged particle bunch traveling, on the average, along a locally rectilinear trajectory. Referring to Fig.1, we take the axis of this trajectory 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 will associate the main bunch dimensions with the quantities $2\sigma_x$, $2\sigma_y$ and $2\sigma_y$. 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

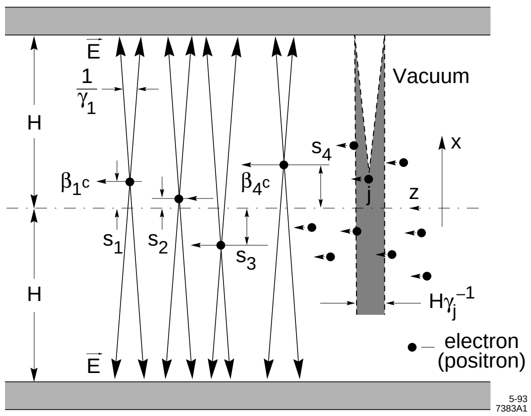

Fig. 1. Parameters of particle bunch in vacuum.

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

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

$$\Delta z_e = H/\gamma_j. \tag{2}$$

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

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

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

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

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

$$\left|\vec{E}(x=H,z)\right|[KV/cm] \cong \frac{0.3N_C qg(z)}{H}. \tag{5}$$

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, in passing, the high energies required for the method to be considered applicable to proton (antiproton) beams. Second, in order to obtain useful fields, there must be a sufficient quantity of particles within one electronic resolution length

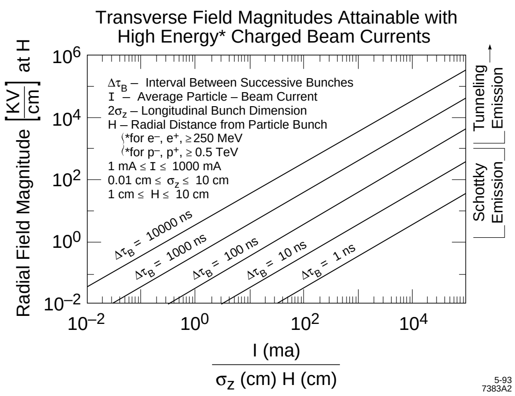

Fig. 2. Field magnitudes and corresponding surface-emission phenomena obtainable from charged- particle bunches.

(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 to be approximately 0.15 μA, with an interbunch interval of 10^7ns and a 60 μ full bunch length, extrapolation of the curves in the graph indicates that field strengths in excess of 2.5×10^3 kV/cm could be attained at a distances of a few mm from the bunch axis.

3 OUTLINE OF EXTENDED METHOD

As schematized in Fig. 3, an essential mechanism of the profiling method is the interaction of a probe photon pulse of full temporal length $(2(\pi)^{0.5}\sigma_{ph}$ with the particle bunch field as they both traverse a suitable medium at a relative lateral displacement H. Whereas in the cited prior work [7,8] surface and bulk interactions with various types of solid-state media were considered, in the present paper we consider the use of a gas. If we assume the group velocity, v_g, of the photon pulse to be different from βc, the particle bunch velocity, and $c\sigma_{ph} << \sigma_B(=\sigma_z)$, 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 $1/(\beta-(v_g/c))$. The function of the gaseous medium is three-fold. First, its pressure and temperature are adjusted to set the group velocity of the probe pule almost equal to the bunch velocity to permit a sufficiently long scanning duration. Second, the pressure and temperature are both

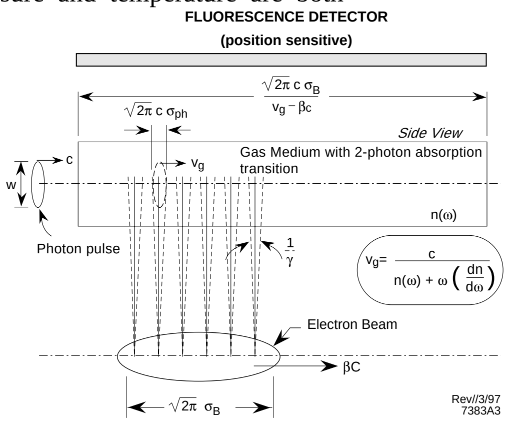

Fig. 3. Interaction of probe laser pulse and electron bunch field in passage through a gas medium

optimized to allow transit of the laser pulse through the interaction length in a "self-focusing" mode [10], which helps the pulse maintain a relatively constant cross section. Third, the gas is chosen to have a resonant or near-resonant two-photon transition corresponding to the laser wavelength. With reference to the above calculations, the strength of the combined fields is sufficient to modulate the two-photon absorption cross sections of the gas [11] via the Stark effect, resulting in a correlation between the absorption at any point in the medium and the strength of the bunch field. Due to parity, the excited atoms will have relatively long fluorescence lifetimes, allowing a conventional position-sensitive detector, installed over the interaction region, to register the intensity of the fluorescence trace. We note that if the use of a gas cell in proximity to the e-beam axis is found to be problematical due to the required dielectric interface to the vacuum, for diagnostic purposes the beam could be deflected into an off-axis gas cell isolated from the vacuum by differential pumping sections.

Table 1. Profiler system parameters. H=2 mm. E=15 GeV, $N_C=10^{10}$. Beam waist w=10 μ.

	Ti:sapphire Pulse	e-beam	Gas Cell (NO_2)
Power^{a,b}[W]	10^{10}	7.5×10^{12}	-
Field [V/m]	2.7×10^{11}	10^{7}	-
Pulse Length [μ]	3	100	-
Bandwidth [%]	33	0.02	-
Group Vel.. Diff. [m/s]	-	-	1.53×10^{4}
Gas Press.[mTorr]	-	-	75
Interaction Length [m]	-	-	2
2-Photon Cross Sect.^{b} [bn]	-	-	10^{5}
Fluoresc.Yield^{b} [Phot./m]	-	-	10^{10}

^{a}Critical power for self-focusing;
^{b}order-of-magnitude estimate

In Table 1 we present a list of nominal operating parameters and performance estimates for a candidate system based on NO_2 [12,13,14]. The figures represent cell performance for the laser pulse only, since the Stark effects on the 2-photon cross sections of NO_2 have not, as yet, been assessed.

4 DISCUSSION

We have presented the analysis of a modulation scheme for the single-shot longitudinal profiling of ultra-short electron or positron bunches based on two-photon absorption induced by an IR femtosecond probe pulse. Figures for a commercially available Ti:sapphire laser and an NO_2 gas medium reveal acceptable performance parameters. Further work is required to quantify Stark modulation effects of the combined laser and electron beams and to investigate other material systems in other wavelength regimes.

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