ACCELERATING AND TRANSPORTING ATTOSECOND AND FEMTOSECOND BUNCHES OF ELECTRONS

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Abstract

Dynamics of short bunches of electrons obtained upon field emission in quasi-static electric field and a variable electric field of a laser has been studied. When the forces of space charge have little effect, grouping part of the beam permits to obtain bunches of about 200-as duration when using carbon dioxide laser and about 6-as with a neodymium laser.

INTRODUCTION

Obtaining short bunches of electrons near the cathode [1,2] inside laser focus can not be an ultimate aim because no experiment could be performed in such a destructive environment: the specimen to be explored or some devices for using electron bunches would be ruined by the high electric field ($10^7 - 10^8$ V/cm) of laser focus. Therefore, it is obvious that electron bunches should be transported out of the laser focus. Employing a quasi-static electric field is essential for accelerating bunches to a sufficiently high velocity and reducing velocity spread in the bunch. The influence of space charge on bunch dynamics has been evaluated (Sect. 3).

ACCELERATION AND TRANSPORT OF BUNCHES

The length of electron bunches obtained by field emission near the cathode is approximately T/8 to T/2, where T is the period of laser oscillations [1]. However, with further acceleration in electric fields and drifting in space free of fields bunches are deformed.

Dynamics of electron bunches was investigated by integrating the equation of motion of electrons. For practical strength of quasi-static and laser electric fields, electrons move with non-relativistic velocities, i.e., $v << c$, where c is the velocity of light in vacuum. This permits to neglect the influence of magnetic field of the laser wave. Therefore, the equation of one-dimensional motion of electrons in the direction of total electric field was used. The longitudinal forces of space charge of the bunch were not considered in the equation (their influence is evaluated in Sect. 3).

We consider the motion of electrons when the cathode spike is at the center of the laser focus. If only the field of the laser wave acts on the cathode spike, emitted electrons oscillate at the wave frequency and the velocity amplitude (in units of the velocity of light in vacuum) $\beta = v_0/c$ is

$$\beta = eE_{0v}/(m\omega) = eE_{0v}\lambda/(2\pi mc^2). \quad (1)$$

Amplitude of longitudinal oscillations is

$$x_{0v} = (\beta\lambda)/(2\pi). \quad (2)$$

For non-relativistic electrons, i.e., $\beta << 1$, it follows

$$eE_{0v} << 2\pi mc^2/\lambda, \quad (3)$$

$$x_{0v} <<< \lambda. \quad (4)$$

This condition for electric field corresponds to $eE_{0v} << 3\cdot10^9$ V/cm for λ = 10 μm and $E_{0v} << 3\cdot10^{10}$ V/cm for λ = 1 μm, which can be satisfied for the problem considered here.

Electrons also acquire a directed progressive velocity that depends on the phase of the field at emission and grows slowly in absolute value (when the emitter is placed at the center of the focus). The average value of energy is characterized by averaged effective potential $mc^2\beta^2/4$ [3], i.e., 5 eV in field $2\cdot10^7$ V/cm at the focus of CO_2 laser (λ = 10 μm) and 3 meV in a similar field of the fourth harmonic of a neodymium laser (0.266 μm). As a result, electrons drift slowly from the point of emission and oscillate with laser frequency according to field amplitude.

In this regime (E_0 = 0), electrons at the beginning of the bunch have a maximal velocity exceeding the minimal (at the end of the bunch) by two or three times. This leads to rapid spreading of the bunch, i.e., increasing its length by 1.5 times when being propagated to the length of the bunch (for a large E_v, owing to oscillations, the second half of the bunch returns to the cathode and is absorbed).

The application of a quasi-static field at the cathode completely changes the dynamics of the bunch: their velocities increase by more than an order of magnitude, velocity spread sharply decreases and the rate of bunch lengthening falls. Moreover, all of the second quarter of the laser field ($\pi/2$ - π) is useful for accelerating and bunching the beam.

If the cathode is at potential V_0, the strength of the electric field on a spike of small radius of curvature ρ_c E_{0n} = V_0/ρ_c (for anode-cathode distance much larger than ρ_c). Electric field E_0 = $V_0\rho_c/r^2$ and the energy of electrons at a distance $r >> \rho_c$ is $\approx eV_0$. For a proper choice of parameters the energy of electrons lies in the range 1 - 50 keV.

With acceleration in the quasi-static field, the spread in energy of electrons is sharply reduced because the kinetic energies acquired in quasi-static and effective ("laser") potentials are additive and the velocity spread in the bunch is

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$\delta v/v = \delta v_l/v_l \times E_l/E_{st}$,
where $\delta v_l/v_l$ is the velocity spread in the bunch without a quasi-static field, and E_l and E_{st} are the energies acquired in effective "laser" and quasi-static potentials whereby the latter is 10^2 - 10^4 times greater than the former.

Fig. 1 presents the evolution of spread in electron velocities in a bunch with $V_0 \neq 0$.

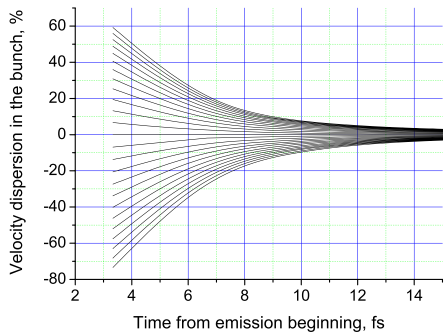

Figure 1: Evolution of spread in electron velocities in a bunch with $V_0 \neq 0$.

Bunching of the second half of the beam due to favorable velocity modulation is shown in Fig. 2 for λ = 10 μm. Bunch evolution is presented in Fig. 3. The bunch with minimal duration is shown in Fig. 4.

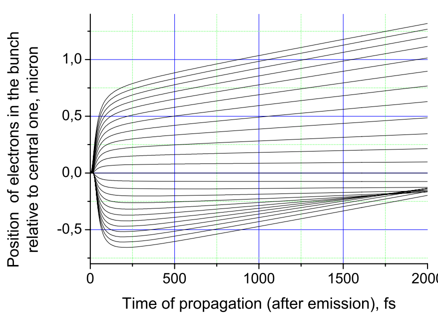

Figure 2: Bunching of the second half of the beam. $E_0 = 6 \cdot 10^7$, $E_v = 10^7$, λ = 10 μm, $v_0 = 2 \cdot 10^8$ cm/s.

Bunch evolution when a 1 μm laser is used is similar to the one in Fig. 3, but the time scale is ten times shorter(Fig. 5). The minimal duration bunch for this case is shown in Fig. 6.

Multi-spike cathodes are necessary to obtain large currents. Laser radiation in this case is directed in the form of a flat wave (or in a wave-guide) parallel to the cathode surface with the electric wave vector perpendicular to cathode plane. Cathodes in the form of spikes or blades must be placed along wave propagation with a period that is a multiple of the laser wavelength (Fig. 2 in [1]). All spikes will emit bunches synchronously. For example, if for λ = 10 μm, on an area of 1 mm^2 there are placed 10^4 cathode

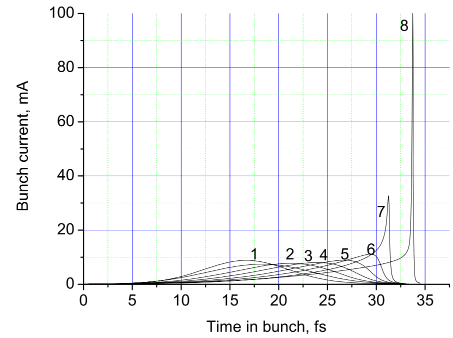

Figure 3: Bunch evolution during acceleration and drift. $E_0 = 6 \cdot 10^7$, $E_v = 10^7$, λ = 10 μm, $v_0 = 2 \cdot 10^8$ cm/s.

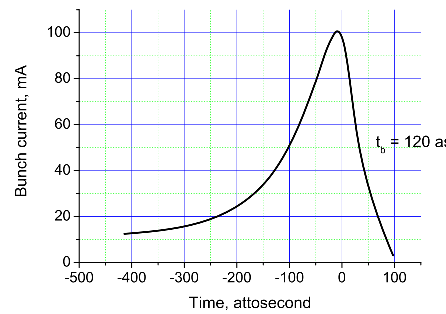

Figure 4: Current in the beam for maximal bunching. Parameters are the same as for Figs. 2 and 3.

spikes of 0.2 μm diameter, it is possible to obtain a total current of 1 - 10 kA when each spike gives 0.1 - 1 A.

The minimal length of a sequence (train) of bunches is TN, where T is the period of laser wave and N the number of spike cathodes along the direction of wave propagation.

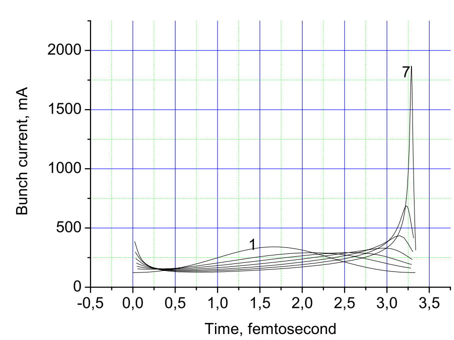

Figure 5: Bunch evolution; $E_0 = 2 \cdot 10^8$, $E_v = 2 \cdot 10^7$, λ = 1 μm

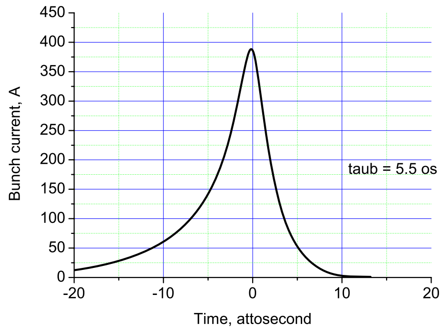

Figure 6: Current in the shortest bunch for Fig. 5.

THE INFLUENCE OF SPACE-CHARGE FORCES, FOCUSING, VACUUM CONDITIONS AND CATHODE PLASMA

Compensating the Action of Space-charge Forces

To simplify calculations, space-charge forces of the bunch (both longitudinal and transverse) were not considered when integrating the equation of motion, but their influence was evaluated separately by considering simplified models, where equation of motion can be integrated analytically, or using the law of conservation of the sum of kinetic and potential energy.

It is easiest to consider a sphere consisting of electrons having zero initial velocity and uniform distribution of charge density. The equation of motion of an electron, which is at radius r_i (initial radius r_{i0}) and accelerated by the force of charge inside the sphere of radius r_i is:

$$m\frac{dv}{dt} = \frac{4\pi}{3} e\rho \frac{{r_i}^3}{{r_{i0}}^2}, \tag{5}$$

where m is the mass of the electron, e its charge, v the radial velocity and ρ the initial density of charge in the bunch (for r_i = r_{i0}.

If the direction of velocities of electrons is reversed (to the center) in the expanding bunch, the motion of electrons in the bunch will be symmetrical for coordinates and antisymmetrical for velocities (to the center and from the center, respectively). Thus, in a moving bunch, the repulsive action of space charge can also be compensated on a length equal to twice the compression length by giving the electrons at the beginning a velocities directed to the center and linearly rising in module from the center to the periphery.

The maximal spread of velocities in a bunch is

$$\frac{\delta\beta_{||}}{\beta_{||}} = \sqrt{\frac{I_{max}}{I_0 {\beta_{||}}^3}}, \tag{6}$$

where I_{max} is the peak current of the bunch, $I_0 = mc^3/e \approx 17$ kA, m the rest mass of an electron, e its charge and c the velocity of light in vacuum. For a current of 1 A and $\beta_{||} = 0.1$ we obtain $\delta\beta_{||} = 0.02$. The evaluation in the problem with a sphere is over-estimated since the bunch is compressed in all three coordinates and the density increases inversely proportionally to the radius cubed.

A more realistic evaluation can be obtained by solving the problem of compressing a bunch in the form of a disc (cylinder). In this case

$$\frac{\delta\beta_{||}}{\beta_{||}} = \sqrt{\frac{I_{max}}{I_0 \beta_{||}^3} \times \frac{d_{min}(d_{max} - d_{min})}{R^2}}, \tag{7}$$

where d_{max} is the length of the bunch before compression, d_{min} after and R the radius of the disc. For a wavelength of 1 μm, R = 0.1 μm and the bunch duration 10 - 100 as, which corresponds to $d_{min} \approx 0.3 - 3$ nm, and assuming $d_{max} = 10 \times d_{min}$, one has $\frac{\delta\beta_{||}}{\beta_{||}} = 10^{-2} - 10^{-1}$, which is quite attainable in certain regimes.

Focusing in the Transverse Direction

The expansion of a micro-beam in the transverse direction has two causes: angular divergence, since the emission surface is part of a sphere, and repelling due to space-charge forces. When a bunch is transported a limited distance, both effects can be compensated by giving electrons close to the spike a radial velocity linearly increasing with radius and directed to the axis. This can be achieved by fitting the geometry of a circular electrode close to the spike coaxially with it and at the same potential [4].

The required transverse velocities of electrons in a bunch can be calculated from the law of conservation of the total energy (sum of the kinetic and potential ones).

$$\beta_{\perp i} = \frac{r_{i0}}{R_0} \times 4\sqrt{\frac{I}{I_0\beta_{||}} \times \ln\frac{r_i}{r_{i0}}} \tag{8}$$

For a current of 160 mA, β_i = 0.007 at the external radius of the beam and the length where the beam diameter does not exceed the minimal by more than 20% is about one wavelength. Such focusing can be also used further on along the beam propagation.

ACKNOWLEDGEMENTS

The author is grateful to O.A.Smith for his help in preparation the manuscript.

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