EVOLUTION OF ELECTRON BUNCHES IN A COMBINED QUASI-STATIC AND LASER ELECTRIC FIELD

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Abstract

Short pulses of electrons of femtosecond and attosecond duration are necessary for numerous applications: studying fast processes in physics, chemistry, biology . Previous calculations revealed that it is possible to obtain such short bunches by applying quasi-static electric voltage to a needle placed into a laser focus. This paper presents results of computer simulation of the electron bunch evolution for various parameters of the problem (quasi-static and laser electric fields, radius of curvature of the needle, velocity of electron emission etc.). The influence of velocity dispersion in the bunch due to the emission process is discussed and a way to optimize the bunching was proposed. Bunch dynamics accounting for space-charge forces was studied using an analytical solution of the equation of motion.

INTRODUCTION

Modulation of electron beams at optical frequencies is promising for numerous applications in physics, chemistry, and biology [1-3]. As it was shown earlier [4, 5], placing a needle cathode biased with a quasi-static potential into the laser focus permits to obtain a train of electron bunches of femtosecond and attosecond duration at the frequency of the laser (e.g., carbon dioxide or neodymium lasers).

The number of bunches in the train can be varied from one to dozens or hundreds by changing the envelope of the laser pulse. Such electron bunches can be used for time-resolved diffraction (structural) analysis of expansion, deformation and destruction of solids under high-power thermal and mechanical loads [6].

After additional acceleration, electron bunches can be applied for generation of tunable, coherent UV and X-ray electromagnetic radiation in the periodic structure of the electromagnetic field.

Moreover, such trains of electron bunches could serve as a relativistic mirror [7]. Interacting with a counter-propagating pulse of electromagnetic radiation (even wide-band), the mirror will select radiation at resonant frequencies and reflect it with frequency multiplication of $4\gamma^2$, where γ is a relativistic factor of accelerated electrons.

Small longitudinal dimensions of bunches (nm) and negligible energy spread $10^{-4} - 10^{-3}$ allow to obtain tunable, coherent UV and X-ray radiation of acceptable power for experiments with micro- and nanoscale objects.

It was shown in previous papers [4, 5] that it is possible to obtain ≈ 10 as pulses with a laser of 1 μm wavelength. Calculations were performed there in one particle approximation and it is necessary to conduct a more detailed study of instantaneous velocity spread, i.e. imitate non-zero phase volume of electron beam. Here electron dynamics is analyzed more thoroughly for various emission velocities as the main cause of dispersion. Quasi-static and laser fields as well as emission velocity influence phase distribution of electrons in a bunch so their strengths were varied to reveal it.

Bunch evolution in a space-charge dominated regime was also studied for two cases: a plane (sheet) bunch and a spherical one corresponding to multi-spike and single-spike cathodes respectively.

BEAM DYNAMICS IN A COMBINED QUASI-STATIC AND LASER ELECTRIC FIELD

Bunch length after emission is a distance between the leading electrons (e.g. at half maximum) and last electrons (also half maximum). The duration τ for small laser electric field compared to quasi-static field $E_v << E_{st}$ may be nearly laser half-period $\tau \approx T/2$, and $\tau \approx T/8$ in the case $E_v >> E_{st}$. The mean propagation (directed) velocity depends mainly on E_{st}, so one can estimate initial bunch length

$$l_b \approx \tau\sqrt{\frac{2eV_0}{m}}, \tag{1}$$

where e, m are electron charge and mass, V_0 is the voltage applied to the spike. One can see this in Fig. 1.

The larger bunch corresponds to small E_v and is approximately half of full swing of the set of trajectories proceeding with phase step $2\pi/24$ rad. Smaller bunch lengths correspond to larger ratios E_v/E_{st} and include less beamlets around the $\pi/2$ phase ($E_v = E_{v0}sin(-\pi/2 + \omega t)$).

Laser electric field produces velocity modulation in the bunch depending on the phase variation from front to back electron emission. Main velocity dispersion is obtained during one-two periods of laser oscillations. Further, there are much smaller changes in velocity spread. This can be seen in Fig. 2, where velocities of electrons versus time in

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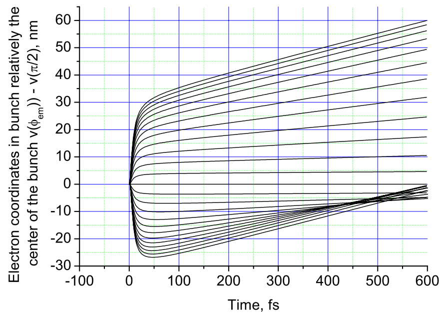

Figure 1: Bunching in the second half of the beam. $E_{st} = 1 \cdot 10^8$, $E_v = 5 \cdot 10^7$, λ = 1 μm, $v_0 = 2 \cdot 10^3$ cm/s.

coordinate system of their electrostatic motion are shown. This system is convenient because it is possible to use velocity distribution in the bunch at any time as starting ("initial") velocities. If no noticeable changes of velocities occur further, one can exclude laser field from the equation of motion when integrating it numerically or even calculate v(t) by just summing "initial" and electrostatic energies:

$$\epsilon = \frac{mv_F^2}{2} + \frac{mv_L^2}{2} + eV_0(1 - \rho_c/(\rho_c + r)), \qquad (2)$$

here ρ_c is cathode tip radius, v_F and v_L Fermi and laser induced velocities. Motion in central static potential is integrated analytically, and that accelerates calculations considerably.

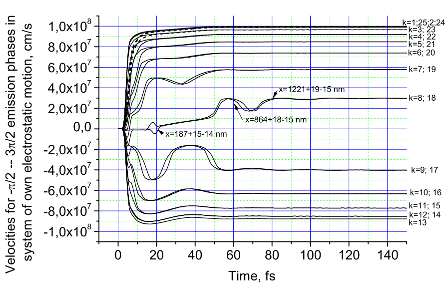

Figure 2: Time dependence of velocities of electrons emitted at various laser oscillation phases; k = 1 corresponds to $\phi = -\pi/2$, k = 25 - $\phi = 3\pi/2$. Field parameters are the same as in Fig1.

Laser excited velocities versus emission phase in electron own electrostatic systems are shown in Fig. 3. The amplitude of curves depends mainly on laser field amplitude (full curve amplitude is nearly proportional to it) and emission velocity. The latter influences curve amplitude somewhat queerly and shifts the curve to lesser phases.

Dependence of electron velocities on emission phase in the coordinate system of the bunch centre is presented in Fig. 4. Velocity dispersion in the bunch is decreasing in time as electrons are accelerated. One can calculate this

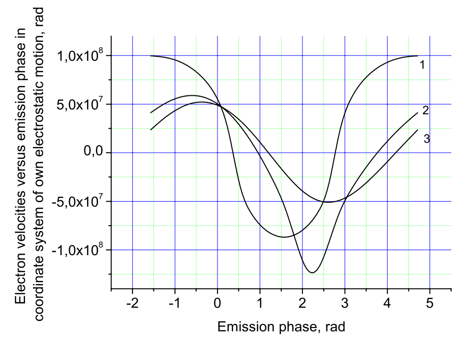

Figure 3: Electron velocities at t = 60 fs versus emission phase for various emissiom velocities. Field as in Fig1.

using (2) in more evident form:

$$v_{ib} \approx \sqrt{v_{st}^2 + v_F^2 + v_{iL}^2} - v_{st} \approx \frac{v_F^2 + v_{iL}^2}{2v_{st}}, \qquad (3)$$

where v_{ib} is electron velocity in bunch, v_{iL} is laser excited velocity of electron emitted at phase ϕ_i.

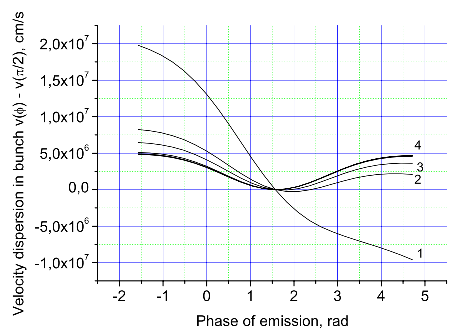

Figure 4: Velocity dispersion in bunch at various times of acceleration in quasi-static field.

Nearly full quasi-static field velocity is acquired for $r >> \rho_c$, and electrons then drift for a long time and distance $r >> \lambda$ not changing velocity significantly. Hence it is possible using (1) and (3) to estimate the time and distance when partial bunch of the beam will reach minimal length. This is beneficial for quick survey of numerous options to choose the optimal one.

It should be noted that a formula given in [8] can not be applied because the condition that laser period should be much smaller than the period T_{st} of motion in potential field $2\pi/\omega << T_{st}$ is not satisfied. Quasi-static field falls sharply $E_{st} = E_0(\rho_c/r)$ with $\rho_c \approx \lambda/10$, i.e., by the factor 3 in 20 fs equal to 6 periods of neodymium laser.

It is necessary to take into account two factors when choosing an optimal set of parameters. First, the minimal bunch length in real beams depends also on instantaneous velocity dispersion. Formula 2 shows that the most favorable may be low velocities. Integration of the equation of motion shows that the time shift between $v_F = 1 \cdot 10^7$ and $v_F = 1.05 \cdot 10^7$ cm/s cases is less than 1 as. Small emission velocities require application of semiconductors for spike material, larger - metals.

Second, curves minima in Fig. 4 move to larger phases with increasing emission velocity. This means (especially for large E_v/E_{st} values) that useful phase region starting from curve minimum slips somewhat out of the most favorable region of bunch current curve $(0 - \pi)$. One can use $\pi/2 - \pi$ phase interval with small emission velocities and $1/3 - 1/5$ of it with large ones. Bunch current at emission for small E_v/E_{st} values has large duration $\approx T/2$ and not big variation of I_{max}/I_{min}. In this case, $\pi/2 - \pi$ interval is also useful. Subsequent bunching compensates bunch lengthening at emission.

SPACE-CHARGE EFFECTS

Bunch length at emission can be of the order of several nanometers to dozens of nanometers. Further shortening of some part of the bunch may increase its maximal current by several orders of magnitude if small instantaneous velocity spread is insured [5]. The limiting factor at this stage becomes space-charge force.

Two models can be studied analytically as the initial step. The first is one-dimensional treatment adequate to a multi-spike cathode which generates a plane (sheet) bunch. The second model is also one-dimensional and suitable for a one-spike cathode. A short emitted bunch can be approximated as a uniformly charged sphere, and this problem has also an easy solution.

The problem for a spherical bunch was treated in [5]. The total beam/bunch current with a multi-spike cathode of area S is S/λ^2 times larger than for a single-spike cathode, e.g., $\approx 10^3 I_b$ for $S = 30 \times 30 \mu m^2$. If a blade-type cathode is used, the current is $I_b S/(\rho\lambda)$, i.e., 10 times larger than for a multi-spike one. The longitudinal dimension of a plane bunch decreases faster and to a smaller value than for a spherical bunch because space-charge force does not increase during bunching contrary to the spherical bunch. Evolution of bunch duration is shown in Fig. 5 for initial bunch peak current $I_b = 0.8$ A of one beamlet (one spike).

POSSIBLE APPLICATIONS

Trains of short electron bunches may be useful for various applications. First, they can be applicable directly for excitation of atoms, molecules and micro- and nanostructures in researches in physics, chemistry, biology and medicine. By varying two-spike cathode geometry, one can obtain two successive bunches with regulated time interval between them to implement the pump-and-probe method.

Second, such beams can be used for time-resolved diffractometry of fast processes of thermal expansion or destruction in high-power-load experiments.

Third, it is possible to generate tunable coherent electromagnetic radiation of UV and X-ray spectra. Such options could be very effective if bunches were accelerated to MeV energies of electrons. This may be done by using modern schemes of acceleration by lasers. One can use further two ways: generation of coherent radiation by bunches in a periodic structure of electromagnetic field created by laser or using such a periodic structure of bunches as a multi-layer flying relativistic mirror.

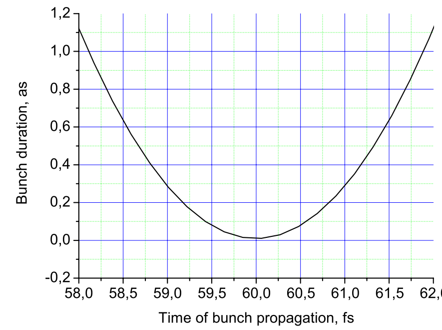

Figure 5: Final stage of plane bunch contraction. $E_0 = 4 \cdot 10^8$, $E_v = 5 \cdot 10^7$, $\lambda = 1$ μm, initial one spike current of 1 fs duration 0.8 A .

Counterpropagating coherent radiation with wavelength λ will be reflected to produce coherent radiation with wavelength $\lambda_r = \lambda/(4\gamma_e^2)$. The necessary requirement for phasing radiation from all bunches is that in an electron comoving system $d' = n\lambda'$, where d' is the distance between the bunches, λ' is the wavelength of radiation $\lambda' = \lambda/(2\gamma)$, and n is an integer.

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