ATTOSECOND AND FEMTOSECOND ELECTRON BUNCHES OBTAINABLE UPON FIELD EMISSION 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 and medicine. Heating of spikes for single-pulse regime is several degrees and therefore it is possible to generate a sequence of electron bunches (up to 100–500 pulses). They can be used in diffractometry and after acceleration to 3–4 MeV for generation of short pulses of VUV and soft X-ray radiation in periodic fields or as a relativistic mirror.

INTRODUCTION

Modulation of electron beams at optical frequencies is promising for numerous applications in physics, chemistry, and biology [1-5]. As it was shown earlier [6 - 9], 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 analysis of expansion, deformation and destruction of solids under high-power thermal and mechanical loads [4].

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 [5]. 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 [6 - 9] that it is possible to obtain $\approx$ 10 as pulses with a laser of 1 μm wavelength if space-charge forces are negligible . Currents of 10 mA to 10 A can be obtained from single-spike cathode and upto 10 kA with a multi-spike cathode. Further bunching occurs due to velocity modulation in the bunch by laser electric field. In this paper, electron dynamics is analyzed more thoroughly for various emission velocities as the main cause of dispersion. Quasi-static and laser fields and 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.

CATHODE GEOMETRIES AND REGIMES OF OPERATION

Wide known Fowler-Nordheim formula was used to calculate currents one can obtain from needle cathode. In the field strength range $3 \cdot 10^7 - 2 \cdot 10^8$ V/cm the density of current from the cathode follows the Fowler-Nordheim law quite well and in the case of a copper cathode for the given field strength range is $1 - 7 \cdot 10^8 A/cm^2$. The formula was obtained for static field but can be applied for variable fields as well if the time of electron tunneling is much less than a period of a periodic electric field [10]. In the case of a combined quasi-static and variable electric field obtaining the exact solution of the Schrödinger equation is very difficult, but the criteria of validity of Fowler- Nordheim formula is the same: the tunneling time of electron should be much less than duration of variable field period.

Evaluating the field strength for copper cathode (barrier height 4.3 eV) and carbon dioxide laser ($\lambda = 10\mu m$) gives $E_{sum} > 10^8$ and $E_{sum} > 10^9$ for neodymium laser ($\lambda = 1\mu m$).

It should be noted that real applied laser fields may be much lower because of field enhancement on the spike tip with small radius of curvature [11].

Fig. 1, 2 and 3 are schematic representation of three types of devices. In 1 a single spike device: a cathode having a spike with a curvature radius ρ_c is at the focus of a laser. A quasi-static voltage V_0 is applied to the cathode. This creates at the spike a high-intensity electric field $E_{0n} \approx V_0/\rho_c$, where E_{0n} is the field perpendicular to the cathode surface (the distance between the cathode and the anode here is considered to be much greater than the curvature radius ρ_c).

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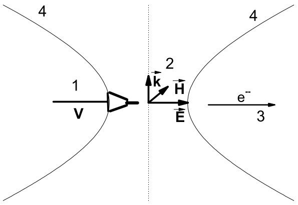

Figure 1: Schematic drawing of the device: 1 - cathode, 2 - EM-wave focus, k - wave-vector, E and H - electric and magnetic vectors of the wave, respectively, 3 - electron beam, 4 - focus surface where E = 0.

The schematic drawing of a multi-spike cathode is shown in Fig. 2. The spikes are placed with a period equal to laser wavelength λ in the direction of laser wave propagation in order to synchronize all electron bunches.

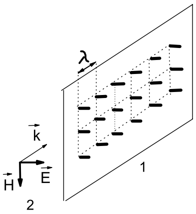

Figure 2: Schematic drawing of the multi-spike cathode: 1 - cathode, 2 - EM-wave , k - wave-vector, E and H - electric and magnetic vectors of the wave, respectively.

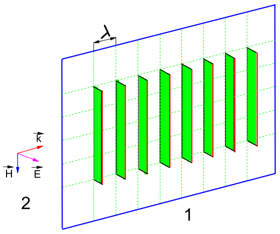

Figure 3: Schematic drawing of the blade cathode: 1 - cathode, 2 - EM-wave , k - wave-vector, E and H - electric and magnetic vectors of the wave, respectively.

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

The length of an electron bunch near the cathode depends mainly on the ratio of amplitude of variable field to the value of quasi-static field, E_v/E_0. 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

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

where e, m are electron charge and mass, V_0 is the voltage applied to the spike. One can see this in Fig. 4 as well as bunching of a part of the beam.

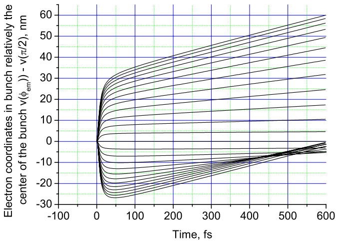

Figure 4: Bunching in the second half of the beam. $E_{st} = 1 \cdot 10^8$, $E_v = 5 \cdot 10^7$, λ = 1 μm, $v_0 = 2 \cdot 10^3$ cm/s.

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. 5, where velocities of electrons versus time in coordinate system of their electrostatic motion are shown.

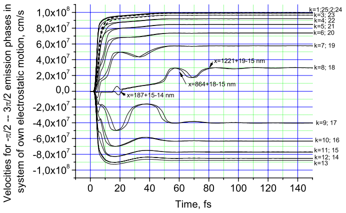

Figure 5: Time dependence of velocities of electrons emitted at various laser oscillation phases; k = 1 corresponds to $\phi = -\pi/2$, k = 25 - $\phi = 3\pi/2$. Field parameters are the same as in Fig4.

It should be noted that a formula given in [12] 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 $E_{st} = E_0(\rho_c/r)^2$ 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. Form.2 [9] 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 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

Two models can be studied analytically as the initial step. The first is one-dimensional treatment adequate to multi-spike or multi-blade cathodes 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 [9]. 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. 6 for initial bunch peak current $I_b = 10$ A of one beamlet (one spike).

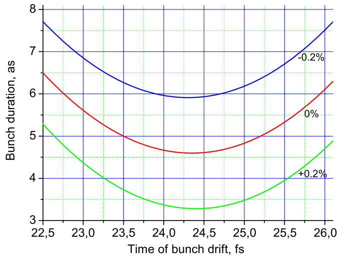

Figure 6: Final stage of plane bunch contraction. $E_0 = 4 \cdot 10^8$, $E_v = 8 \cdot 10^7$, λ = 1 μm, initial one-spike current 10 A of 0.4 fs duration, $\delta v/v = \pm 0.2\%$.

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.

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 λ' = λ/(2γ), and n is an integer.

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