

# FIELD CALCULATIONS TO OBTAIN ATTOSECOND/FEMTOSECOND ELECTRON BUNCHES

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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. Three cathode designs were proposed: a single spike device, multi-spike cathode, and multi-blade cathode. Obtaining short electron bunches of attosecond and femtosecond duration requires combined quasi-static and laser electric field and careful field formation in cathode region. Laser field enhancement on cathode spikes was calculated. Enhancement factors as large as 100 - 1000 can be obtainable allowing to reduce laser power by 10 thousand to 1 million times.

## INTRODUCTION

The schemes proposed earlier [1–5] with electron field emission in a combined quasi-static and laser electric field are here considered in more detail.

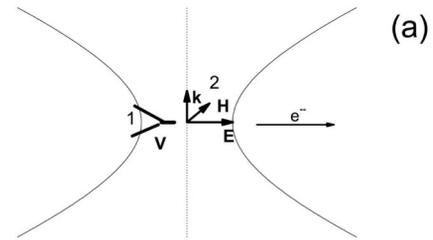
An important role in optimizing a scheme for obtaining short pulses is played by the choice of the geometry of the cathode and the near-cathode region; also, the parameters of laser radiation (plane of polarization and angle of incidence, specific power on the cathode), magnitude of quasi-static voltage etc. In particular, the choice of optimal angle of incidence was derived from Fresnel formulas. An enhancement in quasi-static and laser electric field takes place on spike and blade cathodes. In the present work, more exact calculations are presented. They show that the enhancement of the field can be considerably more ( $10^2 - 10^3$ ).

## SCHEME OF ARRANGEMENT AND SELECTION OF FIELDS

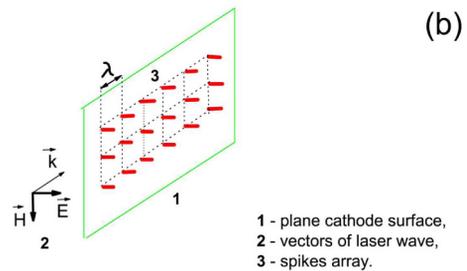
To determine the possibility of experimentally realizing the system, it is necessary to work out the following subjects: 1. geometry of emitter; 2. parameters of quasi-static and laser fields; 3. determination of optimal angle of incidence of laser wave; 4. enhancement of laser field on cathode spike.

Figure 1a shows the scheme with a single-spike cathode. A cylindrical or conical cathode has a rounded end of radius  $\rho_c \ll \lambda$ , where  $\lambda$  is the wavelength of laser radiation. The spike is placed on a flat metallic platform of dimensions much greater than  $\lambda$ . In order to give the bunch a sufficient directed velocity, one has to provide a quasi-static voltage  $V_0$  on the cathode. The intensity of the

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Multi-spike cathode



1 - plane cathode surface,  
2 - vectors of laser wave,  
3 - spikes array.

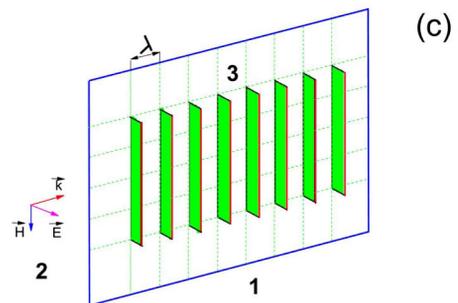


Figure 1: Scheme of Arrangement for Obtaining Short Electron Bunches: 1. Cathode, 2. Electromagnetic wave, 3. Plate;  $\vec{k}$  – wave vector,  $\vec{E}$  and  $\vec{H}$  – electric and magnetic vectors of wave,  $e^-$  – electron beam, (a) – single-spike cathode, (b) – multi-spike cathode, (c) – blade cathode.

normal component of the quasi-static field at the top of the cathode  $E_{n0} \approx V_0/\rho_c$ .

A normal component of electric laser field must be provided to modulate the emitted current. First, this is provided by the choice of p-polarization at an angle of incidence for which the sum of the incident wave and the one reflected from the platform is a maximum. Second,

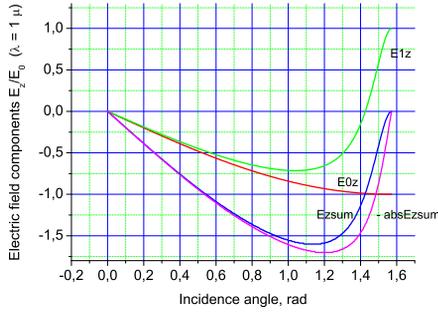


Figure 2: Dependence of the Normal Component of Incident, Reflected and Summed (Incident and Reflected) Laser Field on the Angle of Incidence at the Platform Surface for Wavelengths:  $\lambda = 1 \mu\text{m}$ ,  $\epsilon = 0.35^2 - 7^2 + 2i \cdot 0.35 \cdot 7$ .

for dimensions of cathode spike  $\rho_c \ll \lambda$ , the spikes only insignificantly distort the field of the laser wave in its surroundings, not significantly affecting reflected waves, and for calculation one can apply Fresnel's known formulas using the complex refractive index for metal [6].

Figure 2 presents dependences of normal components of incident, reflected and summed (incident and reflected) electric laser field on the angle of incidence at the surface of a copper platform for wavelengths of  $1 \mu\text{m}$ . It would be advantageous to choose the angle of incidence as  $\theta_0 = \pi/2$  (sliding incidence) to minimize the absorption of energy in the cathode, but then  $E_{z\Sigma} = 0$ . The maximum of total field  $E_{z\Sigma}$  is before the Brewster angle: when decreasing wavelength it decreases and moves in the direction of smaller angles. For copper platforms, the total field (in units of the incident) is 1.9 for  $\lambda = 10 \mu\text{m}$ , 1.7 for  $\lambda = 1 \mu\text{m}$  and 1 for  $\lambda = 0.255 \mu\text{m}$ .

For an angle of incidence that gives a maximum normal component, there is absorbed at  $\lambda = 1 \mu\text{m} < 2.5\%$  of incident energy (while in a beam with photoemission on the fourth harmonic of a neodymium laser  $\approx 100\%$  is absorbed). The problem of heating and damage to the spike in our case should not give concern for two more reasons: a) practically absence of surface currents for close to normal component of field and b) in a pulsed regime for length of laser pulse envelope, for example, 100 fs ( $10^{-13}$  s), heating will be  $10^4 - 10^5$  times less than for a nanosecond pulse for the same current density. It is known that spike cathodes operate successfully at ampere currents of nanosecond length [7].

In the present paper, the external field enhancement was calculated in a static approximation for an uncharged ellipsoid of rotation with half-axis  $a$  and radius  $b$  [8], which is fulfilled here since for the spike  $b = \rho_c \ll \lambda$  and  $a \leq \lambda/4 - \lambda/3$ .

The formula for the enhancement coefficient is:

$$k = E_{max}/E_{laser} = \frac{(1 - b^2/a^2)^{3/2}}{a^2} \times \frac{1}{\frac{1}{2} \ln \frac{1 + \sqrt{1 - b^2/a^2}}{1 - \sqrt{1 - b^2/a^2}} - \sqrt{1 - b^2/a^2}}$$

Figure 3 shows the dependence of  $E$  on the ratio  $b/a$ . For  $\rho_c = 10 \text{ nm}$  and  $\lambda = 1 \mu\text{m}$  ( $a = 250 \text{ nm}$ ) the coefficient of enhancement is  $> 200$ , which allows to reduce laser power  $4 \cdot 10^4$  times. For  $\rho_c = 1 \text{ nm}$ ,  $k = 2 \cdot 10^4$ . The choice of rounding radius of the cathode spike is determined by the required value of current  $I \propto j(kE)\rho_c^2$  and the minimal required laser power.

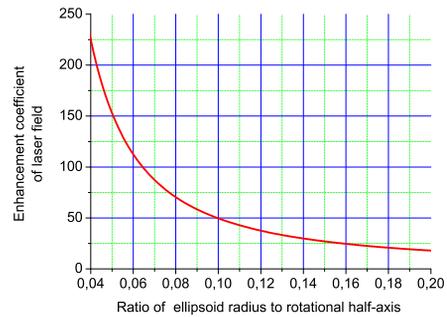


Figure 3: Dependence of Coefficient of Field Enhancement on the Spike for an Ellipsoid of Rotation with Half-axes  $a$  and  $b$ .

Depending on the length of the laser pulse envelope, two regimes of operation of the spike are possible: quasi-static and resonant. In the case when the envelope length  $t_p \gg T$ , field enhancement is possible due to the excitation of electron plasma oscillation in the cathode spike at the resonant frequency [9]. This regime is more suitable for a multi-spike or blade cathode when a longer laser pulse is required.

For a laser pulse length exceeding the required it is possible to use a regime of standing wave with maximum electric field at the center of the focus, and for a yet longer pulse to use a resonator for amplifying field. In a standing-wave regime, the magnetic field becomes zero at the center of the focus, which decreases its influence on the near-axis movement of electrons for lateral dimensions of bunches  $d \approx \lambda/20 - \lambda/5 \ll \lambda$ .

Figure 1b shows the scheme of a multi-spike cathode. In this case, with the proper system of focusing (with possible use also of a laser field), conical beams from each spike are transformed into cylindrical beams of circular cross-section of diameter  $\lambda$ . When the emission current from the system of spikes is modulated, flat bunches of electrons are formed. It is necessary to arrange the spikes in rows with  $\lambda$  spacing in the direction of the propagating laser wave to secure the same phase of electric field for bunches from all

spikes. The laser field in the case of a multi-spike cathode is a flat wave.

When using a traveling wave, the diameter of the cylindrical cathode is determined from the condition that  $2\rho_c \approx \lambda/10$ . The bunch length in this case will be  $\tau_b \approx T/8 + \pi\rho_c/c$ . A decrease in  $\rho_c$  in the same laser field increases the current of the spike,  $I \propto j(kE)\rho_c^2$ , due to a more abrupt dependence  $j(E)$ .

Currents in flat bunches from a multi-spike cathode of area  $\lambda^2 N^2$  (Fig. 1b) are  $N^2$  greater than from a single-spike cathode. For example, when  $\lambda = 1 \mu\text{m}$  and current from one spike is 1A from a platform of  $30 \times 30 \mu\text{m}^2$ , one can obtain a current  $I \approx 1 \text{ kA}$ .

Figure 1c shows a cathode where the vertical rows of spikes are replaced by blades. The current in bunches in this case is increased  $\lambda/(2\rho_c)$  times more than in the case of a multi-spike cathode, and with the same area one can obtain  $I \approx 10 \text{ kA}$ .

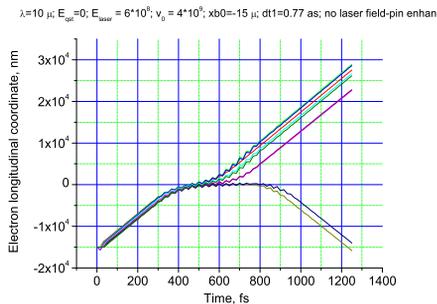


Figure 4: Coordinate on time.  $E_{Lmax} = 6 \cdot 10^8 \text{ V/cm}$ ,  $v_{||0} = 4 \cdot 10^9 \text{ cm/s}$ ,  $\lambda = 10 \mu\text{m}$ ; part of the beam passes through the focus for medium energy of electrons.

It should be noted that in a traveling-wave regime one can obtain double bunches (or a series of several) whose separation can be regulated in time less than a half period of laser wavelength by shifting a second emitter in the direction of wave propagation.

It is natural to place a single-spike cathode at the center of the laser focus. However, while in the homogeneous field of a running wave the emitter can be displaced arbitrarily along the propagation of the wave, in a nonhomogeneous field the location of the emitter is limited. Drift in a spatially nonhomogeneous high-frequency field leads to ejection of particles (bodies) with low velocity from the region of strong field to the periphery. Such behavior was explained as if there were present an “effective” potential with maximum equal to half the kinetic energy of oscillations in maximum field [10].

Injection of an electron of low energy from the region with low field,  $E/E_{max} \ll 1$ , to the maximum (focus) leads to its reflection while maintaining its initial energy. While the initial energy is approximately equal to the maximum of potential, then depending on the phase of injection part of the electrons are reflected and the other part passes

through the focus (Fig. 4). Finally, for higher injection energy, the entire beam passes through the focus.

Though for large fields the quasi-classic approximation may give a less accurate value, the error will not be large when calculated with the Fowler-Nordheim formula. Since the dependence of current density on field is exponential, in experiments the deviation of currents from the calculated ones can be corrected by fine tuning the quasi-static voltage and laser field. An increase of 7% in the intensity of fields approximately doubles the density of current for  $E = 6 \cdot 10^7 \text{ V/cm}$ . If the condition  $\tau_t < T$  is satisfied, replacing  $E_{L0}$  by  $E_{\Sigma} = E_{L0} + E_{qst}$  permits using the Fowler-Nordheim formula for fields up to  $10^9 \text{ V/cm}$ , which corresponds to a current density of  $2 \cdot 10^{11} \text{ A/cm}^2$ .

Corrections in connection with limitations of current due to the action of space charge need not be considered for short current pulses,  $\tau < 10^{-9} \text{ s}$ , since the electric field from a bunch of  $\approx 10^5 \text{ V/cm}$  is much less than external fields even for such current densities.

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