# FEMTOSECOND AND ATTOSECOND BUNCHES OF ELECTRONS UPON FIELD EMISSION IN A COMBINED QUASI-STATIC AND LASER ELECTRIC FIELD

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## *Abstract*

A new method of modulating an electron beam is proposed to obtain electron bunches of 50-as to 20-fs duration. Current from 0.01 to 10 A from one spike having a curvature radius of 1 micron corresponds to a maximal intensity of total electric field of 70 to 180 MV/cm. Obtaining a single bunch or a sequence of bunches with a repetition rate up to 1330 THz was considered. Using multi-spiked cathodes permits to obtain bunches with current up to 10 kA.

## INTRODUCTION

Obtaining short bunches of particles and electromagnetic radiation in recent years has called forth great interest [1 - 8]. This is due to the possibilities of using them in scientific investigations of fast processes in physics, chemistry and biology. Moreover, obtaining a train of short bunches of electrons permits to generate tunable coherent UV and X-ray radiation, transposing to a higher frequency in compact radiators with periodic field structures.

Below there is described a method [9] of obtaining electron bunches from a metallic spike upon simultaneous action on it of two electric fields: a quasi-static and a variable laser field. Analytical calculations and numerical modeling indicate that it is possible to obtain electron bunches of attosecond and femtosecond duration $(10^{-17} - 10^{-14} s)$ with small spread in electron velocities when using lasers having wavelengths in the range 1 – 10 $\mu m$. Using quasi-static voltage permits to increase the average forward velocity of a bunch to transport it for large distances to a region where the quasi-static and laser electric fields are small and do not affect the object being investigated. Moreover, the relative spread of electron velocities in a bunch decreases by more than one order of magnitude, which sharply decreases lengthening of the bunch when transporting.

Forming the envelope of a laser pulse permits to obtain a single bunch or a long sequence of them. Using single-spike and multi-spike cathodes of various configurations, one can obtain currents in the 10 mA - 10 kA range.

Model calculations were performed on transporting electron bunches to distances permitting their use for the generation of ultra-short pulses of radiation in compact radiators with periodic field structures. The influence of space charge on bunch dynamics has been evaluated [10].

## FIELD EMISSION OF ELECTRONS FROM A SPIKE IN A COMBINED QUASI-STATIC AND LASER FIELD

The phenomenon of field emission of electrons (auto-electron emission or tunneling) discovered by R.W.Wood [11] and first calculated on the basis of quantum mechanics by L.W.Nordheim and R.H.Fowler [12], was further investigated by many authors and widely applied. To calculate electron current density $(A/cm^2)$ as a function of strength of electric field E (V/cm) on the surface of a metallic cathode with potential barrier height w (V), we used the Fowler-Nordheim formula:

$$J = 1.55 \cdot 10^{-6} \cdot \frac{E^2}{w} \cdot \exp(\frac{-6.85 \cdot 10^7 \cdot w^{1.5}}{E}) \qquad (1)$$

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 half period of a periodic electric field [13]. Tunneling time depends on the potential barrier height w of the cathode material (ew - work function, eV) and the strength of electric field E on the cathode surface. Since the gradient of potential barrier is usually much higher than the field strength used for field emission, the width of triangular potential barrier for external field E can be evaluated as $d \approx w/E$. Emission current will be modulated if a constant (quasi-static) and a variable electric fields are simultaneously created at the cathode surface. The transit time of an electron through the potential barrier metal-vacuum is $\tau_t \approx d/v_F = w/(E_n v_F)$, where $v_F$ is the Fermi velocity (of electron in metal) and $E_n$ is the total strength of field normal to the cathode surface. The current density will critically depend on the algebraic sum of quasi-static and variable electric fields. The emission current has a maximum when the fields are added and a minimum when the wave field is subtracted from the quasi-static field.

Fig. 1 is a schematic representation of a device for obtaining bunches of femtosecond and attosecond length. A cathode having a spike with a curvature radius $\rho_c$ 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

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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 $\rho_c$). Thus, there simultaneously act a quasi-static electric field and an electromagnetic wave field on the cathode surface exposed to vacuum.

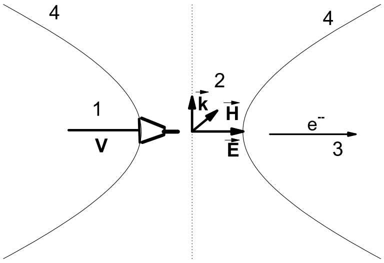

Figure 1: Schematic drawing of the device: 1 - cathode, 2 - EM-wave focus, k - wave-vector, E and H - electric and magnetic vectors of the wave, respectively, 3 - electron beam, 4 - focus surface where E = 0.

The schematic drawing of a multi-spike cathode is shown in Fig. 2. The spikes (or blades) are placed with a period equal to laser wavelength $\lambda$ in the direction of laser wave propagation in order to synchronize all electron bunches. It is necessary to use wave-guided or surface wave to ensure equal field strength on all spikes.

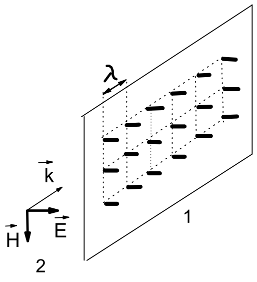

Figure 2: Schematic drawing of the multi-spike cathode: 1 - cathode, 2 - EM-wave , k - wave-vector, E and H - electric and magnetic vectors of the wave, respectively.

For modulation of beam current it is necessary to use p-polarization with vector of electric field in the plane of incidence to have a normal component of laser electric field at the apex of spikes.

For normal incidence on a metal surface (for both polarizations), a wave is in large part reflected and the sign of the reflected wave is opposite to the sign of the incident one. As a result, the field amplitude at the vacuum cathode surface is negligibly small and is directed tangentially to the surface. Therefore, the wave is directed at a small slippage angle $\delta\phi$, the angle of incidence being $\pi/2 - \delta\phi$. The normal components of both incident and reflected waves if $\delta\phi$ does not exceed Brewster angle have the same sign and are summed. So one can gain in acting amplitude of the field compared to the amplitude of the incident wave.

The resultant amplitude modulation of the total field perpendicular to the cathode surface is used to obtain auto-electron emission with deep modulation of beam current. The bunch length is less than a wave period. One can have a single bunch or a sequence of bunches going with laser wave frequency.

To obtain contrast modulation of beam current, one has to decrease the radius of curvature of cathode spikes $\rho_c$ to a dimension less than a half or a quarter of the wavelength $\lambda$ and place the spikes with a period $\lambda$ in the direction of wave propagation to get all micron-size bunches from a single spike to be in phase. The length of the bunch $\tau_b$ can be decreased by decreasing the diameter of the cathode to $\lambda/10$. However, for high duty factors, modulation contrast (ratio of maximal to minimal current) decreases. The spike radius of curvature, therefore, must be determined from the condition

$$0.05\lambda \leq \rho_c \leq 0.45\lambda \qquad (2)$$

The bunch length is

$$\tau_b \approx T/(4\pi) + 2\rho_c/c. \qquad (3)$$

When using a single spike cathode, the spike is placed at the center of the focus of EM-wave. The requirements to the slippage angle remain. It is equal to the angle between the axis (or symmetry plane) of the focus and the plane tangent to the top of the spike.

The advantage of the proposed method is that modulation of the electron beam occurs at the electromagnetic wave frequency, which permits using an EM-wave in a wide range of frequencies, including lasers with quantum energy less than the work function of the cathode material. The use of an IR, optical and UV range permits to increase the modulation frequency to 3–1000 THz and perhaps more and decrease the length of the electron bunches to lengths in the range $\tau_b = 30 - -0.01$ fs and less.

When $\rho_c \leq \lambda/10 - \lambda/5$ the field of the wave for the spike is quasi-static, the acting field strength on the cathode surface is increased locally [14] and the laser power can be decreased. Naturally, the actual value of electric field strength on the cathode surface should be used in calculations with the Fowler-Nordheim formula. The number of electron bunches in the train is equal to the number of periods of wave oscillations with the same amplitude in the EM-pulse and can be changed by varying the parameters of the pulse.

Fig. 3 shows the time dependence of the normal component of the total electric field on the cathode surface when using a neodymium laser and quasi-static voltage on the cathode. Fig. 4 shows the pulses of electron current for fields of Fig. 2.

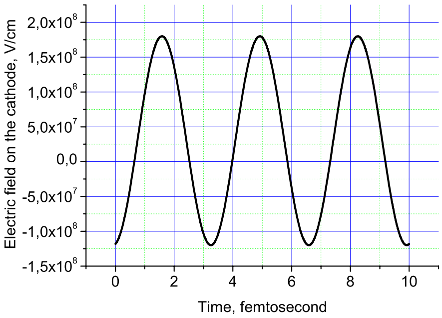

Figure 3: Time dependence of the normal component of the total electric field on the cathode surface; $\lambda = 1\ \mu m$, $\rho_c = 0.1\ \mu m$, $E_0 = 3 \cdot 10^7$, $E_v = 1.5 \cdot 10^8$ V/cm

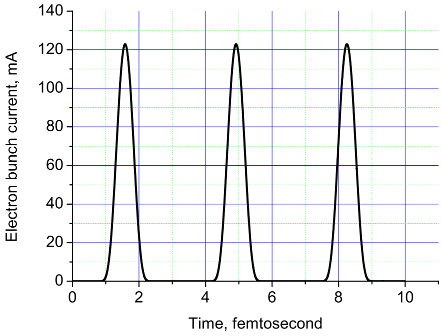

Figure 4: Pulses of electron current for fields of Fig. 3.

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 dependence on maximal value of total field and work function of cathode material acts to a lesser degree. The length of an electron bunch $\tau_b$ as a function of $E_v/E_0$ for copper cathode (ew $\approx$ 4.3 eV) is shown in Fig. 5.

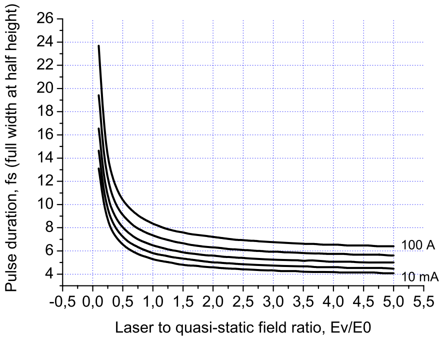

Figure 5: Length of electron bunch $\tau_b$ as a function of $E_v/E_0$ for copper cathode (ew $\approx$ 4.3 eV).

## CONCLUSION

It was shown that it is possible to generate electron bunches of T/2 – T/8 duration. This means that one can obtain bunch lengths from 100 as to 20 fs when using laser waves of fourth harmonic of neodymiun laser to $CO_2$ laser.

It is impossible to use these electron bunches inside the laser focus or near it because of strong laser electric field. Methods tfor transporting and focusing such bunches are discussed in the second paper to this conference [10].

## ACKNOWLEDGEMENTS

The author is grateful to A.V.Vinogradov, L.V.Keldysh, A.N.Lebedev, G.V.Sklizkov and A.N.Starodub for useful discussions.

## REFERENCES

[1] P.Emma,Issues and challenges for short pulse radiation production, Proceedings of EPAC 2004.

[2] C.Hernandez Garcia and C.A.Brau, Nucl.Instrum. and Meth. A 483(2002), 273.

[3] P.Hommelhoff, C.Kealhofer, and M.Kasevich, 2006 Phys. Rev. Lett. 97 247402.

[4] B.Barwick, C.Corder, J.Strohaber et al.,New Journal of Physics, 9 (2007) 142

[5] V. Tosa, H. T. Kim and C. H. Nam,Phys. Rev. A 71, 063808 (2005).

[6] M.Merano, S.Sonderegger, A.Crottini et al., Nature 438, 479 (2005).

[7] H.Ihee, V.A.Lobastov, U.M.Gomez et al., Science 291,458 (2001).

[8] V.A.Lobastov,R.Srinivasan, and A.H.Zewail, Proc. National Acad. Sci. USA 102,7069 (2005).

[9] V.A.Papadichev, A mathod to obtain modulated electron beam, Patent RU 2 269 877 C1, publ. 10.02.06, Bulletin 4.

[10] V.A.Papadichev,"Accelerating and transporting attosecond and femtosecond bunches of electrons", paper to this conference.

[11] R.W.Wood, Phys. Rev. v. 5, 1, pp. 1 - 10, 1897.

[12] R.H.Fowler, L.W.Nordheim, Proc. Roy. Soc. v. 119, 781, pp. 173-181, 1928.

[13] L.V.Keldysh, JETP,47(1964),1945.

[14] Y.C.Martin, H.F.Hamann, and H.K.Wickramasinghe , Journal of Applied Physics 89, 5774 (2001).