METHOD OF BUNCH RADIATION PHOTOCHRONOGRAPHY WITH 10 FEMTOSECOND AND LESS RESOLUTION

ALEXANDER TRON†
Lebedev Physical Institute, Leninsky prospect 53
Moscow, 119991, Russia

IGOR MERINOV
Moscow Engineering Physics Institute, Kashirskoe shosse 31
Moscow, 115409, Russia

The success in creation of the proposed facilities, where the required electron bunch duration can be of about 100 fs and less, will be depend directly on the ability to measure the bunch longitudinal profile with resolution of the order of 10 fs and less. The only method for the bunch monitoring with the mentioned temporal resolution is the method of photochronography of the bunch incoherent radiation, for example, in the frequency range of visible light and at realizing streak camera with new principles of its operation. Results of novel type streak camera design and its investigation with photoelectron dynamics simulation taking into account space-charge effect are presented.

1. Introduction

Longitudinal profile monitoring of electron bunches or x-ray pulses with temporal resolution of the order of 10 fs is playing an increasingly critical role at present when development and creation of accelerator technologies of many applications are aimed at an electron bunch formation with its duration of about 200…100 fs and soft x-ray generation with much less duration [1, 2].

At the same time it is the well-known that a time convert streak camera is the only tool for the measurement with resolution in femtosecond range, the resolution of which in the range of visible light does not exceed 300…200 fs [3], and in the range of soft x-ray, unfortunately, it is near 1 ps [4]

Hence, at present we need the measuring technique exceeding the reached temporal resolution by a factor of 10^2 at least in the case of the mentioned x-ray pulse monitoring. It means that it is necessary breakthrough in the measuring technique like a streak camera that could be made only on the base of new

† atron@sci.lebedev.ru.

principle of its operation. In the paper the results of streak camera design realizing new principles of operation [5] are considered and discussed.

2. Methods of bunch length monitoring

All well-known methods for short electron bunch length monitoring with resolution in femtosecond range may be divided onto two groups: measurements of bunch radiation spectrum in frequency range of coherent radiation with further retrieving of the bunch shape assuming that the spectrum, emitted by a single electron in specific terms of device, is known exactly, - that is not so [6], and second and more reliable method bases on registration the bunch radiation intensity in the frequency range of incoherent radiation by means of streak camera.

Conventional streak camera has limitation in resolution, caused, mainly, by the longitudinal chromatic aberration of the camera' planar accelerating gap, magnitude of which is not less than 100 fs at very narrow initial electron energy spread, of about 0.1 eV, and at using the highest electric field at the photocathode surface in the considered camera type.

Space-charge effect is another reason caused limitation both in temporal resolution and in photoelectron bunch population that, as a rule, does not exceed 20…30 electrons in the cameras of the 300 fs – resolution.

It should be noted also the substantial feature of the conventional streak camera: the accelerating gap is plane-parallel configuration and acceleration of photoelectrons here is most slow; time of flight of the electron bunch from the photocathode to the deflector can reach magnitudes of the order of 1 ns, during of which we have to keep the temporal structure of the photoelectron bunch in spite of space-charge effect.

3. New principles in time convert photochronography

New principle in the time covert photochronography, proposed in [5], consists in the following: the acceleration of photoelectrons and modulation of their dynamic variable in accord with the time of their escapement from photocathode must be performed simultaneously at the moment of this escapement and for the shortest time.

By means of combining the electrostatic accelerating field and rf- field, modulating electron on its longitudinal momentum, in a gap of resonator with internal conductor as a photocathode and taking the radius of the photocathode surface rather small (100…10 μm) one can enhance and localize the field near the surface of emitter so that the time of effective interaction between photoelectron and these fields will be about 1 ps. In the case many effects can not develop for short time, and resolution can reach 10 fs and much less.

Next term for camera realization with the fs-resolution is identical conditions for all electrons starting from different points of emitter. It means that the modulating gap of the camera has to have appropriate symmetry. We will consider here the gap with spherical symmetry.

4. Streak camera realizing new principles of operation

In Figure 1 the possible scheme of the photoelectron camera, realizing new principle of its operation, is shown where the modulated photoelectrons in energy in the gap are analyzed by means of the spectrometer with uniform magnetic field. The rf-gap is formed by appropriate capacity gap of a quarter wave coaxial resonator with its internal conductor being under high voltage potential and ending by needle with a tip in the form semi sphere, covered by a photocathode material. Using the gap as a part of a RF-resonator we suppose that the camera operates in the regime of sinchroscan.

We note at once that at the accelerator beam measurement the rf-power for the camera resonator can be supplied from appropriate rf-system of an accelerator, so that, in the case there is no, in fact, a time jitter between the phase of the RF- field in the gap and the time of photoelectron escapement from the photocathode, and electronic part will be more simple in comparison with corresponding part of a conventional streak camera.

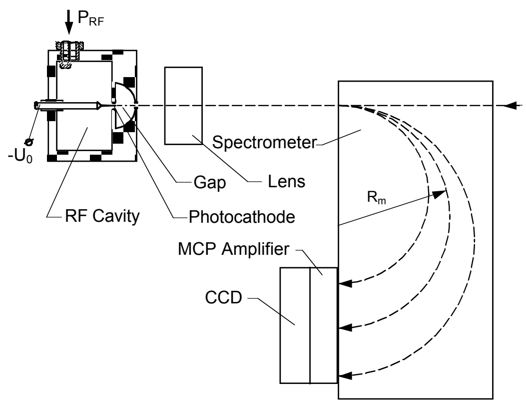

Figure 1. Scheme of streak camera with longitudinal modulation of photoelectrons in the gap of spherical configuration

4.1. *Accelerating gap*

In ideal case a radial electric field in the gap of spherical configuration can be presented by the well-known expression

$$E = E_0(1+m)\frac{R_0^2}{r^2}, \tag{1}$$

where $E_0 = -U_0/h$ – uniform field, when the voltage $-U_0$ is applied to the h-length planar gap; $1+m = R/R_0$ – coefficient of enhancement of the field at the emitter relatively to the uniform field; R_0 – radius of the emitter (internal conductor in spherical capacity gap) and R – is radius of anode (external electrode).

Electrodynamic or modulating field in the gap we will consider in quasistatic approach when the expression for the field can be presented as a product of two functions: one of them depends on the time and another one – on coordinates. Temporal part of field we will write as $f_t = cos(\omega t + \varphi_0)$ where it is assumed that at $\varphi_0 = 0$ the variable $t = 0$.

The modulating field is described in space by the same expression (1) with replacing $-U_0$ on $-U$.

In reality the electric field distribution in space, closed to the ideal distribution, is formed with a diaphragm as it is clear from the Figure 2 where equipotentials of electric field are shown.

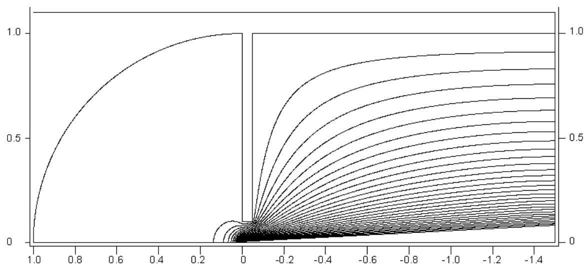

Figure 2. Equipotentials of electric field created by the charged needle shape electrode placed near conducting diaphragm

Axial field distribution in this system is determined by expression

$$E(z) = a_0 z^{-2}(1 + a_1 z + a_2 z^2 + a_3 z^3 + a_4 z^4) \tag{2}$$

Defining the field in units of kV/mm and magnitude of coordinate z in mm the values of coefficients in the expression (2) will be the following: $a_0 = 0{,}2$; $a_1 = 0{,}28152$; $a_2 = -0{,}167428$; $a_3 = 0{,}023894$; $a_4 = -0{,}00106$.

The expression (2) along with the mentioned above coefficients have been determined for the shown system with radius of emitter R_0 = 50μm, radius of anode R = 10 mm and for diameter of the diaphragm hole of 2 mm.

At the voltage U_0 = 4 kV the field on the emitter surface will be 81,087 kV/mm that is very close to the case for the ideal spherical gap. In Fig. 2 the shown boundary equipotential magnitude is 100 V at the emitter voltage 4 kV.

4.2. *Temporal resolution of the camera and its modulating gap*

The proposed method of high speed photochronography is based on two sequential separations of photoelectrons in accord with the time of their escaping from photocathode: first, in the phase space along the longitudinal component of the electron momentum using for that fast changeable field in the gap, and, second, in configurational space by means of electron spectrograph using stationary fields. Hense, the temporal resolution of the camera depends on both the resolution of the modulating gap in the phase space and the resolution of the electron spectrometer (operating in the regime of spectrograph).

4.2.1. Definition of resolution

The time resolution of the camera can be defined by the expression

$$\Delta t_c = \left| \frac{\Delta x}{\partial x / \partial t_0} \right|, \qquad (1)$$

where Δx – width of line at the exit of spectrometer that corresponds to initial electron energy spread, magnitude of which in calculations has been taken from 0 to 0.5 eV: ΔW_0 = 0.5 eV (S-1 photocathode, Ag-O-Cs).

The time resolution of the modulating gap of resonator can be defined as

$$\Delta t_g = \left| \frac{\Delta P_g}{\partial P_g / \partial t_0} \right|, \qquad (2)$$

where ΔP_g – momentum spread of electron at the gap exit corresponding to the initial electron energy spread.

These resolutions are connected through the expression

$$\Delta t_c = \Delta t_g \frac{\Delta P_{spectr} / P}{\Delta P_g / P}, \qquad (3)$$

where the numerator of the quotient is the relative spectrometer resolution, and the denominator – relative momentum spread of the electrons at the gap exit. All magnitudes are determined for the same time of electron start. The quotient

(3) should be never taken less than 1 because by taking the spectrometer resolution ΔP_{spectr} better then the width of the electron momentum line ΔP_g at the gap exit, corresponding to initial electron energy spread ΔW_0 = 0.5 eV, we can never increase temporal resolution of the camera.

4.2.2. Equation of motion

Investigation of longitudinal dynamics of the electrons in the gap, containing the fast changeable in time field, has to be carried out on the base of relativistic equation of motion that could be written in the form [7]

$$\frac{d\vec{v}}{dt} = -e\frac{c^2}{W_e}\gamma^{-1}\left\{\vec{E} + \left[\vec{v},\vec{B}\right] - \frac{\vec{v}}{c^2}\left(\vec{E},\vec{v}\right)\right\}, \quad (4)$$

where e, W_e, c and γ - are respectively an elementary charge, rest energy of an electron, speed of light in vacuum and Lorentz factor; v, E and B – are respectively velocity of the photoelectron, electric field and induction of magnetic field; t – is variable of integration.

We will consider the task in the assumption of ignoring an electrodynamics retardation and description of the field will be in quasistationary approach.

By omitting the space-charge effect at first, there will be considered one-dimensional motion along the z-axis to determine the mentioned above resolutions of the gap and camera.

4.2.3. Temporal resolution dependences

Our investigations show that the gap resolution does not depend practicaly on the gap length $h = R - R_0$ within the range from our R = 10mm and up to 2 mm. The gap resolution mainly depends on the following parameters : R_0, U_0, U and frequency of the modulation field exitation f. Some results of these investigations for f = 3 GHz, R = 10 mm and for initial energy spread of the photoelectrons ΔW_0 = 0.5 eV are presented in Fig. 3 – 7.

It should be noted at once that in all cases, taken for consideration, the field on the photocathode surface does not exceed magnitude $1\cdot10^9$ V/m and in the case there will not be a problem with break-down in the gap after appropriate traning of it similar to prepareing a gun with thermal cathode.

The gap resolution more strongly depends on the photocathode radius. By reducing the radius of emitter up to several microns the gap resolution can reach 1fs and even 0.1fs at consideration of this task in the frame of relativistic classical mechanics, and such resolutions will correspond to the width of the electron momentum line $\Delta P_g /P$ close to $5\cdot10^{-5}$ or $1\cdot10^{-5}$, respectively

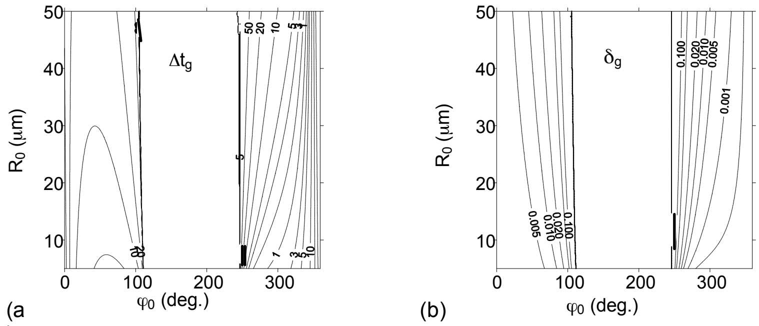

Figure 3. Isolines (in fs-units) of the gap resolution Δt_g (a) and the relative width of the electron momentum line δ_g in percents at the gap exit with parameters: h=10mm, U_0=4kV, U=10kV, - on the plane of variables R_0 and phase of the photoelectron escaping.

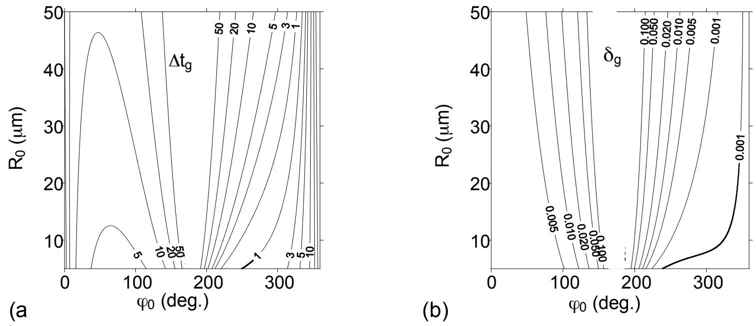

Figure 4. Isolines (in fs-units) of the gap resolution Δt_g (a) and the relative width of the electron momentum line δ_g in percents (b) at the gap exit with parameters: h=10mm, U_0=10kV, U=10kV, - on the plane of variables R_0 and phase of the photoelectron escaping.

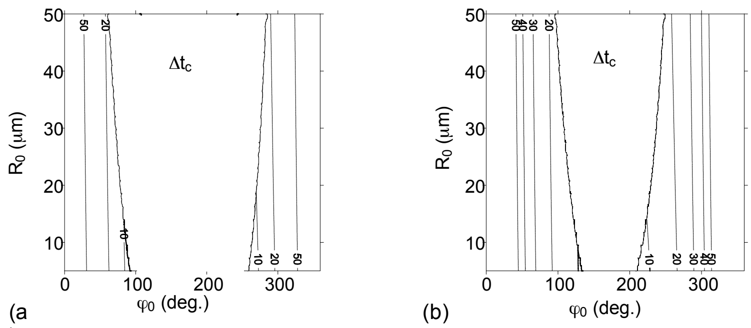

Figure 5. Isolines (in fs-units) of the camera resolution with gap parameter from Fig. 3 (a) and the with gap parameter from Fig. 4 (b) for constant spectrometer resolution of 0.02 % .

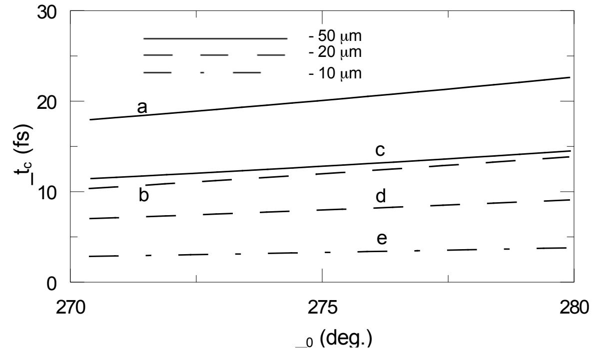

Figure 6. The camera resolution as a function of photoelectron escaping moment in degrees of the modulating field on the frequency of 3GHz for U_0 = 4 kV, U = 10 kV, h = 10 mm at R_0 = 50 μm, 20 μm, 10 μm and for the next spectrometer resolution: $\Delta P_{spectr}/P$ = 0.02 % - ***a*** and ***b***; 0.01% - ***c*** and ***d***; 0.005% - ***e***. The curves e, d, a, c are shifted to the left by 5°, 10°, 15°, 25°, respectively.

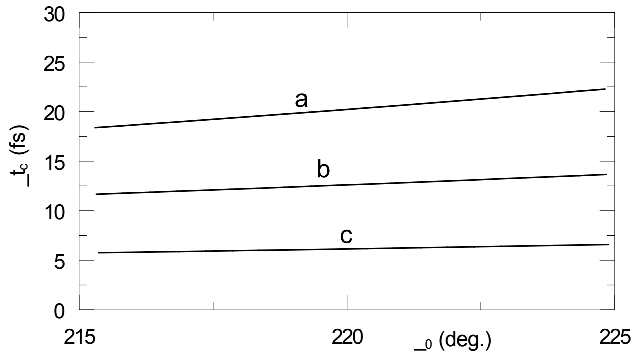

Figure 7. The camera resolution as a function of photoelectron escaping time, expressed in degrees of the modulating field, at the fields on the frequencies: 1.3 GHz (a), 3GHz (b), 11.4 GHz (c),- for U_0 = 10 kV, U = 10 kV, h = 10 mm and R_0 = 20 μm at the spectrometer resolution 0.02 %. The curves b and c are shifted to the left by 15° and 45°, respectively.

From the presented above dependences in Fig. 3-7 one can conclude that the camera resolution is strongly limited by the spectrometer resolution. At rather rough spectrometer resolution (0.02%) the resolution of the camera will be practically the same for the gaps with accelerating voltage of 4 kV or 10 kV. Nevertheless, at these voltages and the spectrometer resolution the camera can reach the10 fs - resolution and in the case we can use the emitter with any radius from 10 μm up to 50 μm. This freedom in option of parameters R_0 and U_0 allows to make further optimization concerning the spectrometer parameters and to mitigate the terms for space-charge effect.

5. X-ray streak camera realizing new principle of operation

Distinction of x-ray camera from the described above one will be mainly in material of the photocathode. For registration soft x-ray with quantum energy from 100 eV to 10 keV the gold photocathode is rather preferable because it is resistive to the air and many other medium. At the same time the initial energy spread in this case has FWHM of energy distribution equaled near 4 eV and quantum efficiency of 6% [8].

If we take the accelerating gap of planar configuration, as in a conventional camera, with its length of 1 mm and accelerating voltage of 10 kV we will have (in the case of gold photocathode) the magnitude of the longitudinal chromatic aberration of 0.7 ps.

It is quite different magnitude will be for the new type of streak camera, scheme of which is presented in Fig. 1, where the chromatic aberration is suppressed due to very high field on the photocathode surface and very small length of effective field, estimated by magnitude of several emitter radii. Moreover, by starting at the same moment and having different initial energy the photoelectron with smaller energy, being in the field increasing in time, can get additional energy in comparisons with other particle so that their initial energy spread can be decreased to the exit gap. It can be watch for definite phase range of their start in the vicinity of 270 degrees where the resolution is the best.

In Figure 8 the x-ray camera resolution in the form of isolines in the fs-units is presented for the modulating gap with parameters: h = 10 mm, $U_0 = U$ = 10 kV, at frequency of the modulating field of 3 GHz and for constant spectrometer resolution equaled 0.01% for picture (a) and 0.02% - for (b).

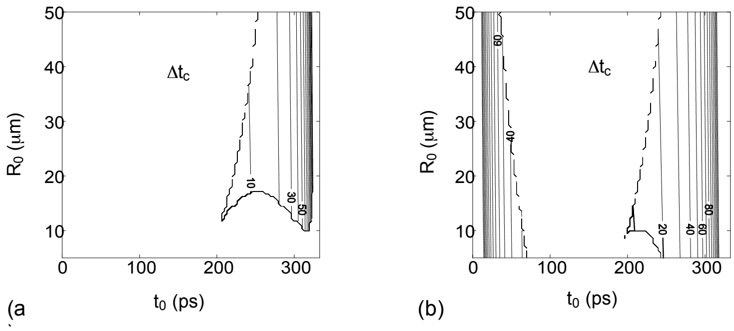

Figure 8. The camera resolution as a function of photoelectron escaping time, expressed in degrees of the modulating field on the frequencies 3 GHz for U_0 = 10 kV, U = 10 kV, h = 10 mm and at the spectrometer resolution $\Delta P_{spectr}/P$ = 0.01 %.- (a), $\Delta P_{spectr}/P$ = 0.02 %.- (b)

6. New type streak camera design

Proposed photoelectron camera, the scheme of which is outlined in Fig.1, has overall dimensions allowing it to be placed on the sheet of format A4.

The modulating gap is a capacity gap of a quarter wave coaxial resonator, schematically drown in the same Fig.1. By taking diameters of internal and external conductors of about 3 mm and 30 mm, respectively, one can get the required amplitude of RF-voltage of 10kV on the gap at pulsed power consumption not more than 100 W on the frequency of 3 GHz.

One of the main units of the camera is spectrometer. There are several types for its implementation meeting requirements of the camera. At this stage of our investigations there has been chosen the simplest spectrometer with uniform magnetic field with semicircular trajectories of electrons in it. To suppress spherical aberration of his type spectrometer the lens is installed at the exit of the resonator.

Figure 9 makes clear operation of this electrostatic lens, where transformations of beam contour in the transverse phase space along optical channel are shown.

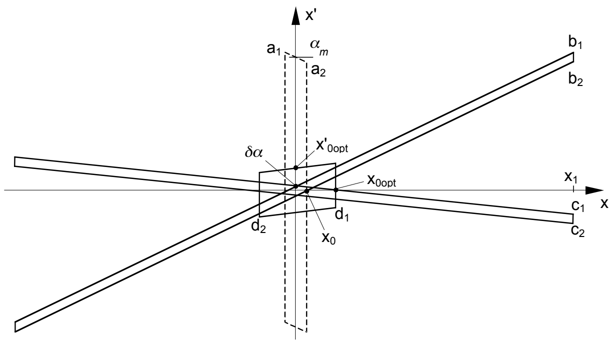

Figure 9. Photoelectron beam contour in the transverse phase space: b_1-b_2 – after the modulating gap; c_1-c_2 – after the lens; d_1-d_2 – at exit drift space, at entrance of spectrometer; a_1-a_2 –equivalent contour in the section coinciding with the center of the photocathode sphere. α_m – semiangle size of the anode hole, taken to be equaled 5°.

In a result of the channel optimization there were obtained the following parameters: x_{0opt} = 10.7 μm, x'_{0opt} = 8 mrad, resolved width of line at the exit magnet is 32μm, spectrometer resolution of 0.02% obtained at the trajectory radius of 80 mm and for electron source x_0 = 1μm, α_m = 5°. Focus length of lens is 9.145 mm, distance between the lens and magnet is about 100 mm. Emittance of the beam does not exceed 0.1 mm·mrad and that magnitude can be made much less in the considered system based on a needle shape photocathode.

7. Conclusion

Considered method of electron bunch radiation photochronography, based on new principles of streak camera operation, allows to carry out measurement of the bunch shape with temporal resolution of 10 fs and much less.

Magnitude of this resolution is independent of frequency range of investigated radiation and it can be used for radiation registration in the rang from visible light to x-ray with the same high temporal resolution.

There was proposed a simple scheme of the device realizing these new principles in high-speed photochronograhpy. It was shown that the mentioned high temporal resolution can be reach at rather low voltages, small RF-power consumption and all device can be placed on the sheet of format A4.

Acknowledgments
Authors thank O. Kozlov of JINR for his help in some investigations of field in the modulating gap.

References

1. Linac Coherent Light Source (LCLS) Conseptual Design Report, SLAC-R-593 (2002).
2. TESLA XFEL, Technical Design Report (Supplement), DESY 2002-167, TESLA-FEL 2002-09 (2002).
3. M.Ya. Schelev, *Physics – Uspekhi* **43** (9) 931 (2000).
4. Z. Chang et al., *Proc. of SPIE* **2869,** 971 (1998).
5. A.M. Tron, *Proc. of SPIE* **4948,** 141 (2003).
6. A.M. Tron, *Proc of PAC99 Conf*. 2190 (1999).
7. L.D. Landau, E.M. Livshits, *Field Theory. Theoretical Physics*. V.2, Fizmatgiz, Moscow, 1963.
8. B.L. Henke, J.A. Smith, *J.Appl.Phys*. **48,** No.5, 1852 (1977).