NEW GENERATION STREAK CAMERA DESIGN AND INVESTIGATION

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Abstract

The only method for electron bunch duration monitoring with resolution of the order of 10 fs and less is the method of photochronography of the bunch incoherent radiation in the frequency range, for example, of visible light and at realizing streak camera with new principles of its operation [1]. In the paper the streak camera design for measuring both the electron bunches and x-ray pulses with the mentioned temporal resolution is presented. The results of the camera investigation with photoelectron dynamics simulation taking into account space-charge effect and influence of the surface roughness of a spherical photocathode of the 20-50 micrometers radius (forming a modulating gap of spherical configuration) on the camera resolution are presented and discussed.

INTRODUCTION

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 of monitoring the bunch longitudinal profile with resolution of the order of 10 fs and less.

All well-known methods for short electron bunch length and shape 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 [2] and that can be extend to any type coherent bunch radiation.

The second and more reliable method is the method based on registration of the bunch radiation intensity in the frequency range of incoherent radiation by means of technique like a streak camera.

At the same time it is the well-known that a time convert streak camera is the only tool for monitoring the bunch radiation 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 for the mentioned x-ray pulse measurement. 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 principle of its operation.

In the paper the streak camera design realizing new principles of operation [1] is considered.

The results of investigating a space-charge and photocathode surface roughness effects are presented and discussed too.

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NEW PRINCIPLES IN TIME CONVERT PHOTOCHONOGRAPHY

New principle in the time covert photochronography, proposed in [1], 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.

CAMERA DESIGN

In Figure 1 the possible scheme of the photoelectron camera, realizing new principle of its operation, is shown where the photoelectrons, modulated in energy in the gap, are analysed with the spectrometer. The rf-gap is a capacity gap of a quarter wave coaxial resonator with its internal conductor ending by needle with a tip in the form semi sphere, covered by a photocathode material.

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, and electronic part will be more simple in comparison with corresponding part of a conventional streak camera.

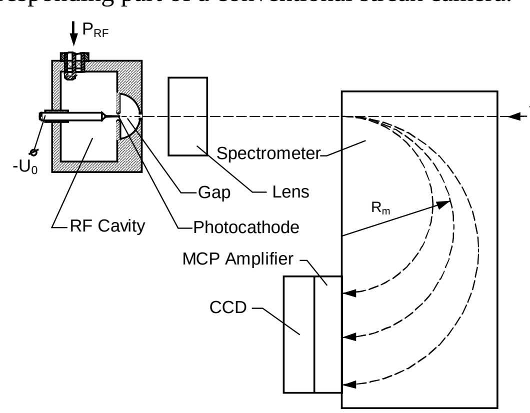

Figure 1. Scheme of streak camera with longitudinal modulation of photoelectrons in the spherical gap.

Temporal resolution of given camera for different spectrometer resolutions and at the resonator excitation on frequency of 3 GHz is shown in Fig. 2 and Table 1.

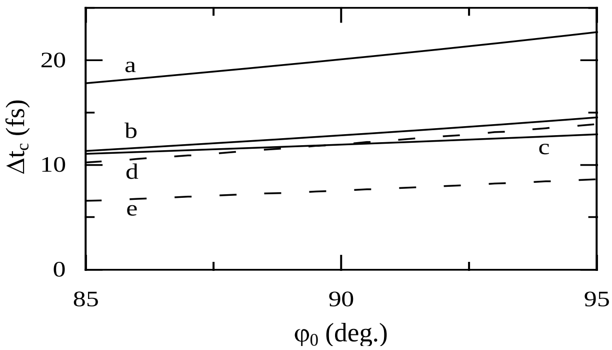

Figure 2. The camera resolution as a function of photoelectron escaping moment in degrees of the modulating field on the frequency of 3GHz for the initial photoelectron energy spread from 0 to 0.5 eV, the anode radius of 10 mm and the others parameters listed in the Table below. The curves **a**, **b**, **d**, **e** are shifted to the left relative to the **c**-line by 20°, 30°, 5°, 13°, respectively.

Table 1: Parameters of the cameras, resolutions which are presented in Fig. 2

N	R_0 (μm)	U_0 (kV)	$\Delta P_{spectr}/P$ (%)	minΔt_c (fs)	φ_{0opt} (deg.)
a	50	4	0.02	16.7	102.5
b	50	4	0.01	11.3	115
c	50	10	0.01	10.8	83.5
d	20	4	0.02	9.88	89
e	20	4	0.01	6.37	97

Here R_0 – radius of photocathode; U_0 – electrostatic voltage on the gap. The modulating field is presented here as $E\cos(2\pi ft + \varphi_0)$.

It should be noted that for the resolution estimation a rather moderate parameters of the camera have been taken and the resolution can reach the magnitude much less. More in detail about that and the camera design one can find where else [5]. Below we shall consider the camera with parameters, marked as variant “b”.

SPACE-CHARGE EFFECT

Space charge effect in the camera realizing new principle operation has been investigated in detail with self-consistent bunch dynamics simulation by representing the bunch as an assembly of charge rings, by solving the system of relativistic Newton’s equations for a given assembly of 100 - 1000 macroparticles and by ignoring an electrodynamics retardation in description of the fields. Space charge effect during the emission has been taken into account via determination of the fields at escaping each following slice of the bunch during all time of its emission. The fields are calculated at each time step of integration. The created code realizing the above mentioned model allows to carry out the required bunch dynamics simulation in conservative fields (in the drift region, for example) with accuracy of conservation of the bunch internal energy within about 0.001% and less [6].

Expression for the macropaticle field is determined via Green’s function for a corresponding boundary problem. The expressions for potential Φ and field components, defined in the point (s, z), that are generated by the charge ring, placed in point (s_i, z_i), are presented below where the s-axis is a axis of longitudinal motion of the ring, the centre which coincides with the s-axis:

$$\Phi(s,z;s_i,z_i) = B\sum_{n=1}^{3}\frac{C_n}{\sqrt{a_n+b_n}}\mathrm{K}(k_n), \quad (1)$$

$$E_s(s,z;s_i,z_i) = Bs\sum_{n=1}^{3}\frac{C_n f_n}{(a_n-b_n)\sqrt{a_n+b_n}}\mathrm{E}(k_n), \quad (2)$$

$$E_z(\vec{r};\vec{r}_i) = Bz\sum_{n=1}^{3}C_n\left[\frac{(1-g_n a_n/b_n)\mathrm{E}(k_n)}{(a_n-b_n)\sqrt{a_n+b_n}}+\frac{g_n\mathrm{K}(k_n)}{b_n\sqrt{a_n+b_n}}\right], \quad (3)$$

where $B \equiv q_i/(2\pi^2\varepsilon_0)$; q_i – charge of the ring; $K(k_n)$, $E(k_n)$ – complete elliptic integral of the first and second kind, respectively; $k_1 = [2b/(a+b)]^{1/2}$; $k_2 = [2d/(c+d)]^{1/2}$, $k_3 = [2d_1/(c_1+d_1)]^{1/2}$ – modules of the elliptic integrals; $C_1 \equiv 1$, $C_2 \equiv -R_0/r_i$, $C_3 \equiv -R/r_i$; $a_1 \equiv r^2 + r_i^2 - 2ss_i$; $b_1 \equiv 2zz_i$; $a_2 \equiv r^2+(R_0/r_i)^4 r_i^2 - 2(R_0/r_i)^2 ss_i$; $b_2 \equiv 2(R_0/r_i)^2 zz_i$; $a_3 \equiv r^2+(R/r_i)^4 r_i^2 - 2(R/r_i)^2 ss_i$; $b_3 \equiv 2(R/r_i)^2 zz_i$; $f_1 \equiv 1 - s_i/s$, $f_2 \equiv 1 - (s_i/s)(R_0/r_i)^2$, $f_3 \equiv 1 - (s_i/s)(R/r_i)^2$; $g_1 \equiv z_i/z$, $g_2 \equiv (z_i/z)(R_0/r_i)^2$, $g_3 \equiv (z_i/z)(R/r_i)^2$; n =1 – for own bunch charge, n = 2, 3 – for the charges, induced in the photocathode and anode, respectively.

At modelling the initial 200 fs- bunch is divided in time on 9 slices during its start. Each slice is divided in angle: within the angle of 0°-5° relatively of the s-axis on 15 cells, within 5°-60° - on 10 and within 60°-90° - on 5. At the start the uniform charge distribution was taken in time and up to 60° after that it drop down to zero on cosine-type low. The analysed part within 0°-5° contained 135 macroparticles.

In Figure 3 dependences of total field and field from the bunch only in the point of placing a head particle nearest to the s-axis during its flying through the gap are shown.

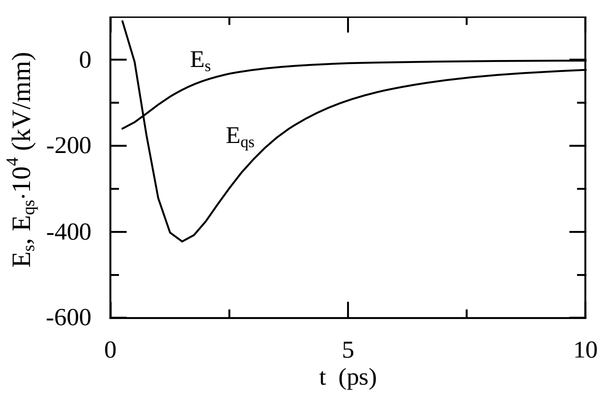

Figure 3: Dependences of total field, including static, alternative field and also from space charges of the bunch with 10^3 electrons, E_s and field of the bunch only E_{qs} on time of flight of a head particle nearest to the s-axis, in point which the fields are defined.

Checking the field of the macroparticle assembly is carried out by comparison its potential energy and fields with values for uniform charged ellipsoid, the potential energy which can be determined exactly by expression: $W_\varphi = (2/5)N\Phi(0)$, where the potential in the bunch centre is $\Phi(0) = (\rho/2\varepsilon_0)M_0$, and potential form-factor are $M_0 = r_b^2(1-M_\parallel)+(l_b/2)^2 M_\parallel$, and at $r_b > l_b/2$ $M_\parallel = \{1 - [(1-e^2)^{1/2}/e]\mathrm{arcsine}\}/e^2$, $e = [1-(l_b/2r_b)^2]^{1/2}$.

By taking the bunch in the form ellipsoid with uniform density and with radius and length of 4 μm and 0.20545 μm, parameters which are very close to what the bunch has in our camera gap, we can check the chosen grid for the bunch modelling. For the mentioned above grid the noted bunch containing 137 rings will have the potential energy of 327.5 eV at the bunch population of 1000 electrons, and the calculated magnitudes, obtained with the formulas, – 333.8 eV and $\Phi(0) = 0.834$ V that differs in energy not more than 2 %. It should be noted that the total internal energy of the tested bunch during the 10 ns-time of its motion integration have changed not more than within 0.005%.

In Figure 4 the dependence of the camera resolution on bunch population is shown taking into account the initial energy spread within 0-0.5 eV . From Fig. 4 one can conclude that the camera allows to operate in the regime from bunch to bunch or in the regime of single shoot.

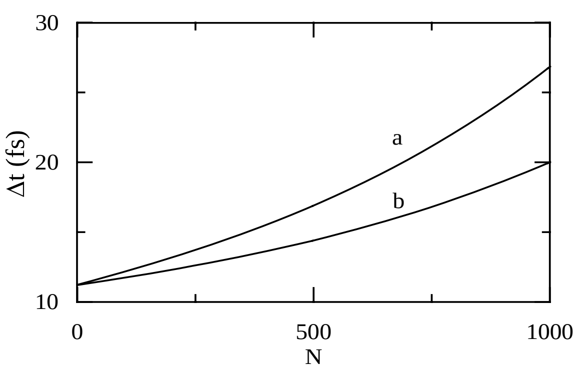

Figure 4: Dependences of the best and worse temporal resolution within the bunch of the 200 fs- initial duration on the bunch population for the camera with parameters of the b-variant in Table 1.

PHOTOCATHODE ROUGHNESS EFFECT

By means of statistical tests the temporal resolution of the camera, taking into account an initial energy distribution of the photoelectrons as parabolic one from 0 eV to 0.5 eV, and angular distribution as a cosine-cube type, has been determined for the photocathode surface roughness with its rms slope of 0.3 [7]. For the following rms height of the roughness: 10 nm, 5 nm, 3 nm and 0 nm, the temporal resolution will respectively be: 21 fs, 16 fs, 12 fs and 5 fs. The resolution have been defined here as ratio of a twice standard of electron distribution in the r-component of the electron momentum at the exit of the camera gap to the derivative of outlet momentum of the electron with respect to its time of start.

CONCLUSION

From the considerations, outlined in the paper, one can conclude the following:

the considered camera for 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 less;

magnitude of this resolution is practically independent of frequency range of the investigated radiation [7] and it can be used for the radiation registration in the range from visible light to x-ray with the same high temporal resolution;

the high current camera allows to operate in the regime from bunch to bunch or in the regime of single shoot;

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 [5] and all device can be placed on the sheet of format A4.

for getting temporal resolution not worse 20 fs in streak camera with new principles of operation, in the case of registering pulses both of visible light and x-ray radiation, the rms height of roughness must not exceed 10 nm [7].

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