

New principles for beam measurements with nm- and fs-resolution

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Realization of ultra-short time interaction between photoelectrons and analyzing field, including both the stationary and rf-modulating field, for photochronography with fs-resolution (of about 10 fs) and registering of secondary electrons, escaping from the smallest part of emitter, for the measurement with nm-resolution are considered.

PACS Codes: 29.27.Fh, 06.60.Jn, 41.85.Ew, 41.85.Qg

1. INTRODUCTION

The success of tuning, optimization of appropriate beam parameters in the future linear colliders (LC), FELs will be defined directly by the ability to measure the longitudinal and transverse bunch charge distributions with the 10 fs- resolution and in the range of several nanometers, respectively [1].

The most promising way for the bunch length monitoring with the mentioned resolution is the method of chronography of the bunch radiation in the range of visible light [2].

We note, realization of this photochronography would allow also to solve many problems at researches in the fs-time scale of ultra-fast phenomenon in the different disciplines of the physics, chemistry and biology [3].

The main tool here was, so named, a streak camera, resolution of which, unfortunately, does not allow to reach the desired resolution in principle [4].

In the paper new principles of photoelectron camera construction, allowing to overcome the mentioned limitation of a conventional streak camera, are proposed and considered.

Next challenging problem is the beam profile measurement near the IP, where the desired resolution exceed that available from the laser interference pattern system [1]. In the paper new secondary electron method for the beam measurement with resolution in the nm-range and its limitation, caused by space charge effect, are also considered.

2. HIGH SPEED PHOTOCHRONOGRAPHY

High speed photochronography is based on use of a time converting photoelectron camera, streak camera. It should be noted 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 inhering in a streak camera, and its electronic part becomes much more simple in comparison with corresponding part of a conventional streak camera.

The principle of operation of the conventional camera consists in the following sequences actions: conversion of an input light pulse into the photoelectron one at the photocathode, acceleration of these electrons till the mesh in the static and nearly uniform electric field, focusing of this electron flux onto the screen and sweeping the flux along the screen with placing a rf-deflector between the focusing lens and the screen.

It is substantial here what all actions are performed sequentially, the accelerating gap is a plane-parallel configuration, time of flight of the electron pulse in the device is rather large and then transverse rf-modulation

is used. As a consequence, we have here, respectively, magnitude of longitudinal chromatic aberration not less than 100 fs at very narrow initial electron energy spread, of about 0.1 eV, strong space charge effect, restricting the time resolution up to 10 fs even at electron spacing equaled to the mentioned resolution [4], dependence of the resolution on the electron position within the cross section of the beam at the entrance of the rf-deflector and, finally, broadening of electron wave packet up to 10 fs due to quantum mechanics effect [4,5].

Hence, summation of all these effects gives us limiting resolution that is not less than several tens femtosecond for a conventional streak tube, in principle. For solving our task for the LC beam there has to be other approach for creation of convenient photochronograph.

A. New principle of camera operation

New principle of camera operation, proposed here, consists in the following.

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

Next term for realization camera with the fs-resolution is the identical condition for all electrons starting from different points of emitter. It means that the modulating gap of the camera has to have appropriate symmetry. For simplicity we will consider the gap with spherical and cylindrical symmetry.

B. Ways of camera realization and its resolution

In Figure 1 the possible scheme of the camera, realizing new principle of its operation, is shown where the modulated photoelectrons are analyzed by means of the spectrometer with uniform magnetic field. As an example, here the rf-gap is formed by a coaxial resonator with its internal conductor, covered by a photocathode. The other possible way of the gap realization is the use of a cylindrical or coaxial resonator with its internal conductor like a point and covered also by material of the photocathode.

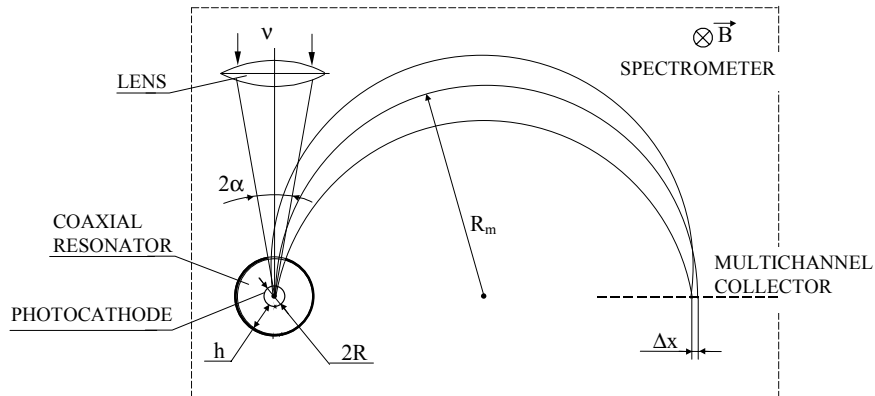


FIG.1. Scheme of camera.

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

$$\Delta t_{\text{div}} = \left| \frac{\Delta \mathbf{x}}{\partial \mathbf{x} / \partial \varphi_0} \right| \quad (1)$$

where $\Delta \mathbf{x}$ – width of line at the exit of spectrometer that corresponds to initial electron energy spread, magnitude of which in calculations has been taken from 0.2 eV to 0.7 eV.

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

$$\Delta t_{\text{res}} = \left| \frac{\Delta(\mathbf{Pc})}{\partial(\mathbf{Pc}) / \partial \varphi_0} \right| \quad (2)$$

Where $\Delta(\mathbf{Pc})$ – momentum spread of electron corresponding to the mentioned initial electron energy spread.

These resolutions are connected through the expression

$$\Delta t_{\text{div}} = \Delta t_{\text{res}} \frac{\Delta(\mathbf{Pc})_{\text{spectr}} / (\mathbf{Pc})}{\Delta(\mathbf{Pc})_{\text{res}} / (\mathbf{Pc})} \quad (3)$$

where the numerator of the quotient is the spectrometer resolution, and the denominator – relative momentum spread of the electrons at the gap exit. This quotient is never less than 1.

In figure 2 and 3 the gap resolution in time as function of the electron entrance phase are shown, respectively, for the gap with spherical symmetry and in the form of the coaxial resonator. Here, R_0 – radius of the emitter surface, h – the gap length, U_0/U_{\sim} - ratio of the static accelerating voltage, applied to the emitter, to the amplitude of rf-voltage, all of them in the kV –units.

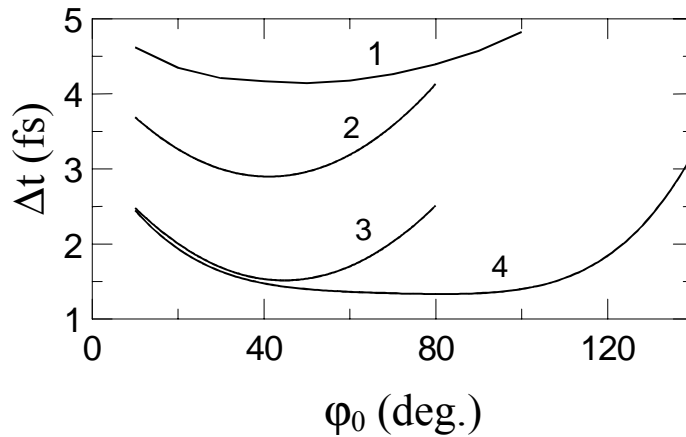


FIG.2. Time resolution of spherical gap vs. φ_0 in degrees of the 11.4 GHz – frequency for the cases: 1 – $R_0 = 25 \mu\text{m}$, $h = 5 \text{ mm}$, $U_0/U_{\sim} = 10/10$; 2 – $R_0 = 2.5 \mu\text{m}$, $h = 5 \text{ mm}$, $U_0/U_{\sim} = 1/10$; 3 – $R_0 = 2.5 \mu\text{m}$, $h = 1 \text{ mm}$, $U_0/U_{\sim} = 1/10$; 4 – $R_0 = 2.5 \mu\text{m}$, $h = 5 \text{ mm}$, $U_0/U_{\sim} = 10/10$.

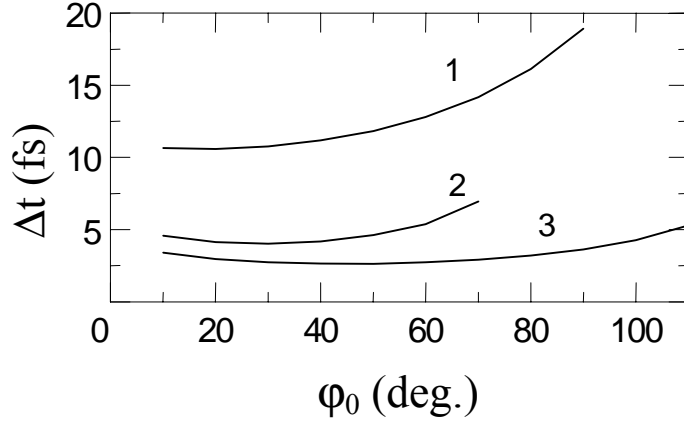


FIG.3. Time resolution of coaxial gap vs. ϕ_0 in degrees of the 11.4 GHz – frequency for the cases: 1 – $R_0 = 25\mu\text{m}$, $h = 5\text{ mm}$, $U_0/U_{\sim} = 10/10$; 2 – $R_0 = 2.5\mu\text{m}$, $h = 5\text{ mm}$, $U_0/U_{\sim} = 1/10$; 3 – $R_0 = 2.5\mu\text{m}$, $h = 5\text{ mm}$, $U_0/U_{\sim} = 10/10$.

C. Quantum limits

The standard quantum limit for measurement error of the electron momentum at the exit of our modulating gap (resonator) due to a back fluctuation action of the meter (thru the field of the gap) on to a quantum system (photoelectron) under test can be estimated thru the well-known relation [7]

$$\Delta E \cdot t \geq \hbar, \quad (4)$$

where $\Delta E = (v-v_0) \Delta P_q$, and $v \gg v_0$.

Hence, $\Delta P_q \geq \hbar / (vt)$, where $\hbar = 0.6582 \cdot 10^{-15} \text{ eV} \cdot \text{s}$, v – velocity of the electron at the exit of the gap, t – effective time interaction between the field and electron that is about 1 ps in our case.

The ΔP_q – fluctuation will be less than 0.001 eV/c. Momentum spread $\Delta P(\phi_0)$ at the gap exit is in excess of ΔP_q by a factor of 10^3 .

The wave packet of an electron has a finite length in time Δt_q that determines its energy uncertainty from other well-known relation [8]

$$\Delta E \cdot \Delta t_q \geq \hbar. \quad (5)$$

At $\Delta t_q \sim 1 \text{ fs}$ the Δt_q - magnitude will be $\sim 0.5 \text{ eV}$ that is comparable with the initial electron spread, taken for the determination of the Δt – resolution of the gap.

The other quantum effect is the delusion of an electron wave packet for the time that can be described as in the paper [9]. Estimation of this effect through the classical equation of electron motion gives additional momentum spread at the gap exit of about $1 \text{ eV}/c$.

From this consideration one can conclude that in our case the quantum limit on the time resolution lays in the region of 1 fs and it can be smaller at reducing the emitter surface radius, for example.

3. WIRE SCANNER BEAM SIZE MONITOR

The spatial resolution of the conventional wire scanner is defined by the smallest practical wire diameter of $4 \dots 8 \text{ }\mu\text{m}$, for example. To increase spatial resolution significantly one can offer the wire scanner with novel principle of operation. This scanner is presented schematically in Fig. 4, the principle of operation is rather clear from which.

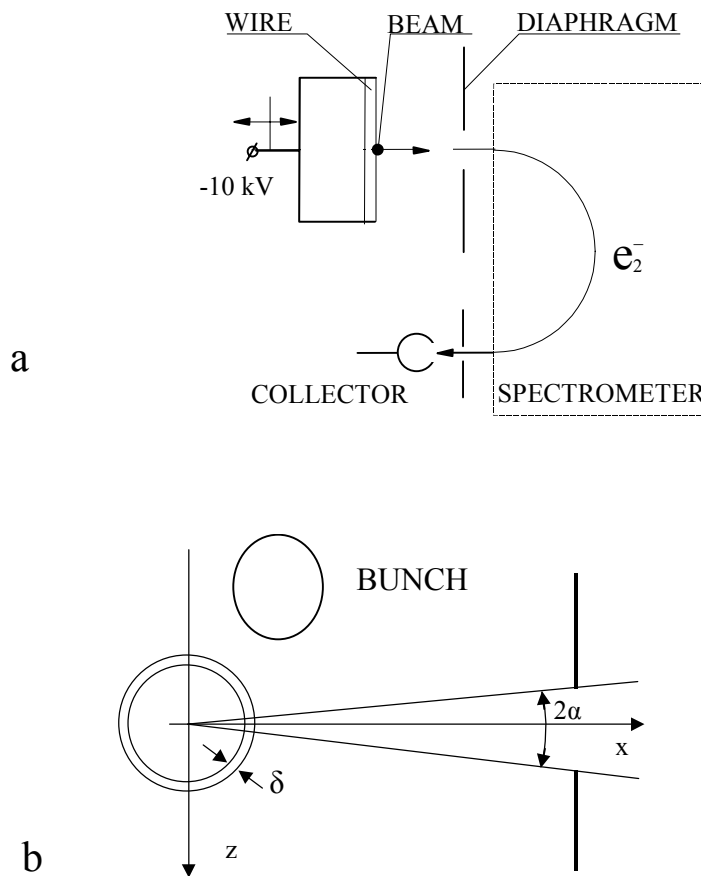


FIG. 4. Wire scanner (a) and its view in more large scale (b).

The basic limitation on the spatial resolution here is the δ - thickness of the region, within of which escaping secondary electrons are produced. The δ - thickness is about several nanometers. The main factor limiting the scanner resolution are the wire heating in a result of the beam energy loss in the wire material and the space charge effect of the accelerator beam.

The later factor was estimated by simulation of the secondary electrons dynamics in the field of the charged cylindrical emitter of the $8 \text{ }\mu\text{m}$ – diameter at the potential of 10 kV and the field of an ellipsoidal bunch with parabolic line charge profile. The simulation results obtained for the spherical bunch with the $50 \text{ }\mu\text{m}$ -radius and

the bunch charge of 1 nC are presented in Fig. 5. In the frame of the consideration one can conclude the error of the bunch size estimation will not exceed $1 \mu\text{m}$ at its measurement on the density level not higher than 0.2.

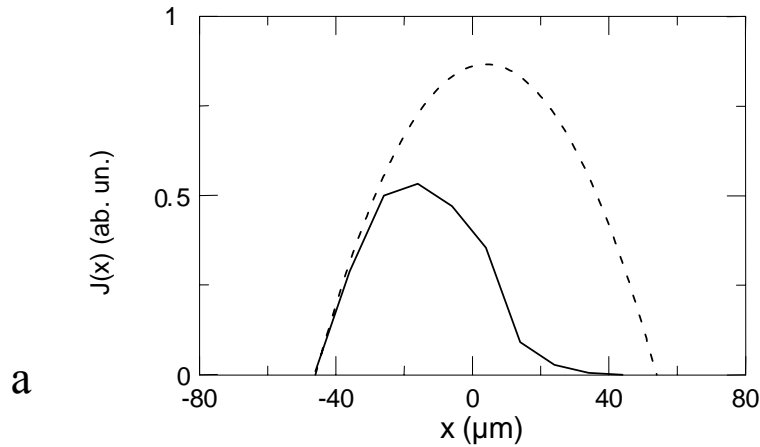


FIG 5. Beam profiles obtained in a result of measurement simulation with bunch space charge effect (solid line) and without it .

At lower beam charge density this technique can reach limiting resolution that is determined by the mentioned layer of the electron escaping.

4. CONCLUSION

Proposed photoelectron camera, realizing new principal of its operation, allows to get the 10 fs-resolution that is far from its quantum limits (1 fs). Option of the camera configuration (spherical or coaxial) mainly depends on desired resolution, its term of operation and can be finally made after consideration and optimization of its parameters taking into account of space charge effect, light spectrum for registration, appropriate objective lens.

Proposed beam size scanner, realizing new principle of its operation, allows to carry out the beam measurement with the spatial resolution not less than $1 \mu\text{m}$ in the case of the bunch charge of 1 nC and its rms radius not less than $5 \mu\text{m}$. This technique could be used as a sample technique complimenting other one that could be created in the nearest future for the beam measurement with several nanometers resolution.

Acknowledgments

Author thanks I.G. Merinov for his help with numerical calculations and V.D. Mur, V.F. Tregubov for useful discussions.

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