

# X-RAY STREAK CAMERA OF 10 FS RESOLUTION FOR XFEL

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## Abstract

X-ray streak camera, based on new principle operation, with resolution of 10 fs for the XFEL project is considered. Main its characteristics and construction features are presented and discussed.

## INTRODUCTION

XFEL facilities, created at present for getting intense x-ray pulses of 200-100 fs duration, need corresponding measuring tool. The only such tool is an x-ray streak camera, but at present its resolution is nearly 1 ps.

### Main limitations in conventional streak camera

Typical scheme of conventional streak camera, shown in Fig. 1, has an accelerating planar gap, length which, marked as the  $h$  – length, is about 1 mm, and time of photoelectron flight till the deflector of the order of 1 ns.

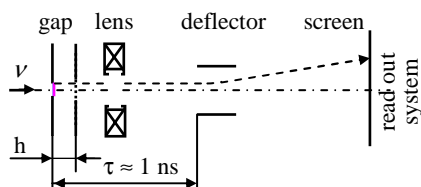


Figure 1: Scheme of conventional streak camera.

Here the resolution is mainly restricted by longitudinal chromatic aberration of the accelerating gap and space charge effect. In Table 1 magnitudes of the aberration for the gap at voltage 10 kV and for two typical initial energy spreads of photoelectrons: 0.1 eV at visible light illumination and 4 eV – for gold photocathode, illuminated by x-ray of 1-10 keV, - are presented.

Table 1: Longitudinal chromatic aberration of planar gap for initial energy spread 0-0.1eV and 0-4 eV.

$U_0 = 10 \text{ kV}, h = 1 \text{ mm}$		
$\Delta W_0$ (eV)	0.1	4
$\Delta t_{ch}$ (ps)	0.1	0.7

For these two cases the best resolution  $\Delta t$ , reached at present and at bunch population not exceeding the marked magnitude  $Q$  (due to the space charge effect), are presented in Table 2.

Table 2: The best resolutions  $\Delta t$ , reached at present.

Streak camera	$\Delta t$ (ps)	$\leq Q(e)$
FESCA 200 (S-1, S-20)	0.2 [1]	20 [2]
X-ray camera (Au)	0.9 [3]	50 [4]

In the case of European XFEL main requirements to the x-ray camera are the following: temporal resolution has to be at least of 20 fs at single hoot regime of the camera

operation and at recording temporal distributions of x-ray pulses, going with frequency up to 5 MHz, without superimposing. Moreover, taking into account time-jitter effect of 1 ps, the number of recording channels has to be not less  $10^2$ . Hence, we need the measuring x-ray technique, exceeding the reached temporal resolution nearly by a factor of  $10^2$  along with increasing the photoelectron bunch population by an order.

It should be noted some papers, issued last time [5, 6], where it is stated of creating x-ray streak camera with resolution of much less than 0.9 ps, reached in work [3] earlier, and operating also with gold photocathode. In the work of LBNL [6], for example, the camera has been calibrated with UV pulses, obtaining the initial energy spread of 0.5 eV instead of 4 eV for x-ray illumination and, consequently, the camera resolution was obtained of 230 fs. The chromatic aberration is proportional to square root from the initial energy spread, so that at the spread 4 eV the resolution will be not less than 0.7 ps at using gold photocathode, that is mentioned in the paper [6], and at the same parameters, listed in Table 1. We note that these works [5, 6] have not been directed on decreasing the chromatic aberration and increasing the bunch population that can be reached on the base of new principle of camera operation.

One can note also statements concerning possibility of creating streak camera with attosecond resolution, but the authors do not explain how they intend to overcome the quantum limit on finite sizes of an electron wave package in time  $\Delta t_q$  and in energy  $\Delta E_q$  that defines the electron energy uncertainty  $\Delta E_q$  or energy spread from the well-known relation [7]:  $\Delta E_q \cdot \Delta t_q \geq \hbar$ , where  $\hbar = 0.6582 \text{ eV} \cdot \text{fs}$ .

## STREAK CAMERA WITH NEW PRINCIPLES OF OPERATION

Method of time convert photochronography, realized in a streak camera, consists in separating photoelectrons along one of their dynamic variables in accord with the time of escapement from photocathode, using for that fast changeable field, and further separation in configurational space, using stationary fields or drift space.

### New principles in photochronography

New principles [8] consist in transformation of the time of photoelectrons escapement from photocathode into one of their dynamic variable that must be performed at the moment of the escapement and for the shortest time, i.e. the transformation has to be performed at the photocathode surface, and this transformation must be identical for all photoelectrons, starting from different points of emitter, i.e. fields in the gap must have appropriate symmetry, for example, spherical or cylindrical in volume, occupied by photoelectrons.

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## New principles realization

New principles, noted earlier, have been formulated by the author in 1975 and for getting resolution much less than 1 ps they have not been requested in practice till 1998 when he offered some approaches for the principles realization. One of them was offered to realize the camera for the XFEL project that is outlined in the paper.

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 (20-100  $\mu\text{m}$ ) 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, mentioned above in the case of a conventional camera, can not develop for short time, and resolution can reach 10 fs and much less. Then temporal resolution will be defined by quantum limit [8] and escaping time dispersion that will be much less than 10 fs in our case.

## Camera scheme

In Figure 2 the scheme of the camera for XFEL, 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. In our case it is gold.

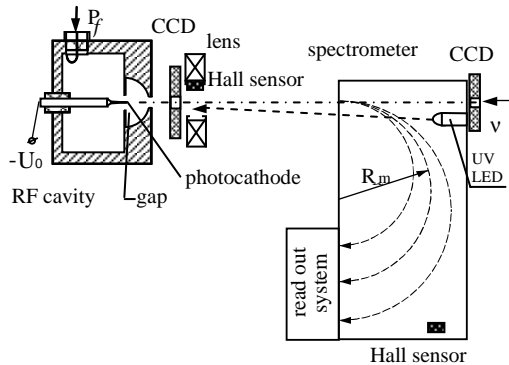


Figure 2: Scheme of the camera for XFEL.

Here the magnet lens with permanent magnet and coil for varying its field within 10% is completed with magnetometer. Maximum field on the lens axis is 0.11 T; FWHM of the field distribution is about 10 mm; distance between the photocathode and plane of the lens symmetry is 20 mm and crossover – 80 mm.

Magnet spectrometer of 0.01% resolution with uniform field (up to 0.01 T) and radius of mail trajectory 80 mm also contains permanent magnet, coil and magnetometer.

X-ray CCD matrixes are required for aligning the camera and estimating x-ray flux. The UV LED illuminates photocathode in the regime of the camera tuning. The read out system as a chip with 256 channels has pixels size in plane of temporal resolution of 16  $\mu\text{m}$ .

## Temporal resolution

Temporal resolution of the camera is mainly defined by resolutions of its gap and spectrometer [8]. The camera resolution with the gap parameters in the Table 3, marked number 3, and spectrometer with resolutions, marked in hundredth percent, is shown in Fig. 3.

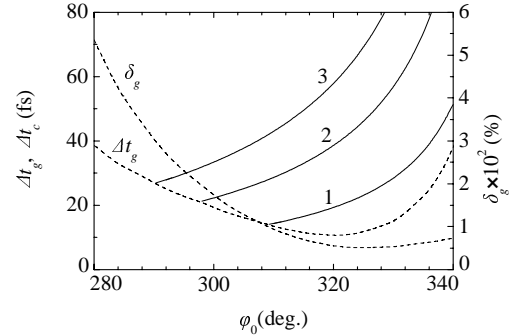


Figure 3: Dependences of camera gap resolution  $\Delta t_g$ , camera itself  $\Delta t_c$  and relative momentum spread  $\delta_g$  at the exit gap vs. photoelectron phase start. Camera resolution is represented by solid line and at the left from minimum it is as a dash line, coinciding with gap resolution.

In Table 3 parameters and characteristics of 3 gaps are presented where  $R_0$  (in  $\mu\text{m}$ ),  $R$  (mm) – radius of cathode and anode,  $U_0$ ,  $U$  – static accelerating voltage and amplitude of modulating voltage on 3.9 GHz in the gap,  $E_0$ ,  $E$  – maximal static and alternative fields at the cathode surface in kV/mm,  $\Delta t_g$  – the best resolution and  $W$  – electron energy at the exit gap, corresponding  $\Delta t_g$ .

Table 3: Parameters of the camera gaps.

N	$R_0/R$ $\mu\text{m}/\text{mm}$	$f$ GHz	$U_0/U$ kV	$\Delta t_g$ fs	$E_0/E$ kV/mm	$W$ keV
1	100/10	3.9	0/20	11.2	0/202	17.74
2	100/10	3.9	8/20	8.2	82/202	24.86
3	100/10	3.9	6/15	10.5	61/152	18.30

The resolutions were obtained, taking into account of initial cosine-cube angular distribution of photoelectrons and initial energy distribution from paper [9, 10]. The resolutions in Table will be of 15 fs at bunch population of 500 electrons due to space charge effect [11].

Photocathode surface roughness has an impact on the camera resolution [12], and, for example, for getting temporal resolution not worse 20 fs the rms height of the roughness must not exceed 10 nm.

One can see that the high resolutions are reached at strong fields at the surface. As to the field of 60-80 kV/mm, marked in the Table 3, it should be emphasized that the magnitudes are not in contradiction with published results concerning breakdown [13, 14].

Time window of the camera, within which the resolution changes not more than on 10%, is 7 ps. It means that, by taking the camera temporal resolution 10 fs or 20 fs at the spectrometer resolutions of 0.01% or 0.02%, respectively, the window allows realize up to 500-300 channels in the read out system.

### Camera construction

Main unit of the camera is photogun that is shown in Fig. 4, where vacuum part of the resonator is drawn only and all sizes - in mm. In should be noted the photogun with new principles of its operation allowing to form monochromatic bunches by means of klystron-type bunching and with negligible time-jitter effect [15], but here it operates, reserving photoelectrons spectrum, obtained at the photocathode surface.

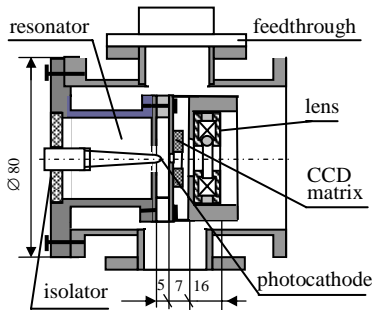


Figure 4: Photogun of the camera

At the left from the isolator there are another part of the cavity where coupling loops for microwave feeding and detection are placed, being under atmosphere pressure. The vacuum part is sealed off, but for getting and maintaining vacuum on the level of  $1 \cdot 10^{-8}$  Torr there is a pump VaClon Plus 20, mounted on the bottom flange.

### Principal new photocathode

Novelty of proposed photocathode consists in both spherical configuration and new material - thoriated tungsten with work function 2.6 eV and up to 2 eV, taking into account Schottky effect in our case. For getting this photocathode the technology, developed by the author in 70-s, will be used, allowing to get stationary voltage 60 kV/mm without discharge that was used earlier in monitor for ion bunch phase distribution measurements [16], where the thoriated tungsten was used as material of secondary electron emitter. The new photocathode will allow to carry out the camera calibration on laser bench, operating with 20-10 fs pulses on 2-d harmonic of a Ti:Sa generator.

Gold-plated phorocathode, technology which has been developed already [17], will be also used. Its quantum efficiency in the x-ray energy rage 0.1-12 keV is not worse 5% [9, 10].

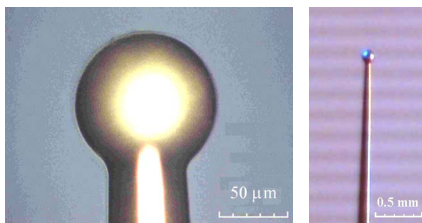


Figure 5: Gold-plated photocathode with the 50- $\mu$ m radius before polishing (left) and conical steely holder of the spherical photocathode before its gold plating.

### CONCLUSION

For investigating ultra fast phenomena, based on recording x-ray flux in femtosecond time scale, there was proposed a principal new streak camera of 10 fs resolution that is developing for the XFEL project at present, some results which were outlined in the paper.

The camera system, offered for XFEL, consists from 3 parts, including mainframe, unit of the camera feeding and laptop.

The mainframe sizes are not more than: 160 mm – in width, 250 mm – in height, 320 mm – in depth. The camera weight is about 15-20 kg.

### Consortium

Consortium for creating the x-ray streak camera for XFEL includes the following organizations: Lebedev Physical Institute of RAS, Moscow Engineering Physics Institute (State University), Federal State Unitary Enterprise “Istok” and Federal State Unitary Enterprise “Experimental Factory of Scientific Engineering”.

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