Design and first tests of miniature K010X soft X-ray streak and single-frame camera

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ABSTRACT

Description of a new K010X soft X-ray camera and the first results of it tests carried out in Russia and China are presented. In a streak mode the full sweep time for a 2 cm sweep route length on the image converter screen is from 2 ns up to 600 µs. In a single-frame mode the corresponding frame duration is from ~10 ns up to ~ 660 µs. Spatial resolution in a single frame mode was not less than 5 l.p./mm for soft X-ray radiation and not less 10 l.p./mm for UV radiation. Spatial resolution in a streak mode for soft X-ray radiation was from 5 up to 10 l.p./mm and for UV radiation on all the sweep ranges was not less than 10 l.p./mm, except for the range of 1 ns/cm where it was 5 l.p./mm. Limiting temporal resolution for UV radiation was near 10 ps and a dynamic range was 200 when full sweep time was 60 ns.
The camera has small 430x115x200 mm dimensions, 5.0 kg weight and 10 VA power consumption.
Key words: image converter tube, camera, X-ray, UV laser, spatial and temporal resolution, dynamic range.

1. INTRODUCTION

The camera is intended for recording and measuring spatial-temporal parameters of high-speed phenomena in the field of soft X-ray and UV radiation in a single-frame mode and a streak mode of sweeping the image under study. The image at the output of the image converter tube (ICT) is recorded with the aid of a CCD readout unit (1392x1032 pixel, 12 bit ADC, USB 2.0 output) and is entered into a personal computer. Software provides the user with wide possibilities of processing the image recorded.
Possible fields of application are: laser physics, nuclear physics, plasma physics including thermonuclear synthesis, electrical breakdowns and discharges, etc.

2. CAMERA PRINCIPE OF OPERATION AND DESIGN

Fig. 1. K010X camera.

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2.1. Block diagram

A block diagram of the camera is given in Fig. 2.

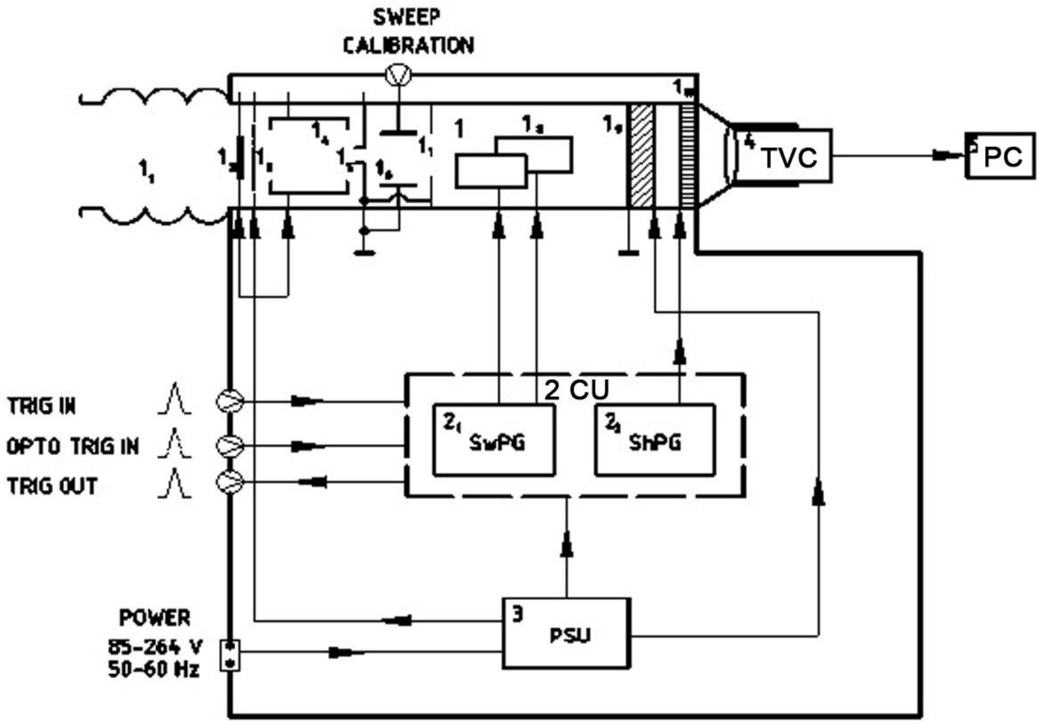


Fig. 2. A block diagram of the K010X camera.

1 - PV-204XM time-analyzing ICT (1_1 - bellows, 1_2 - changeable photocathode, 1_3 - accelerating electrode, 1_4 - focusing electrode, 1_5 - anode, 1_6 - first pair of deflection plates, 1_7 - shielding diaphragm, 1_8 - second pair of deflection plates, 1_9 - MCP, 1_{10} - screen), 2 - control unit (CU), including 2_1 - sweep pulse generator (SwPG) and 2_2 – shut pulse generator (ShPG), 3 - power supply unit (PSU), 4 - CCD television camera (TVC) of readout unit, 5 - personal computer (PC).

An image converter path of the camera is formed by an open (being evacuated during operation) time-analyzing ICT 1 of a PV-204XM type. A readout unit CCD television camera 4 together with a PC 5 forms a digital image-recording system.

Radiation (or a projected process image) recorded by the camera is converted into an electron image on an ICT 1 photocathode 1_2, is accelerated and focused on an MCP 1_9 input surface by an electric field of an electrostatic lens formed by an accelerating electrode 1_3, focusing electrode 1_4 and anode 1_5 ; the electron image intensified in the MCP is transferred to a luminescent screen 1_{10} where it is converted into a visible image. The MCP is used as electronic shutter of the ICT.

The luminescent screen 1_{10} of the ICT 1 is deposited on a fiber optic disk. A photocathode electron current can be increased by at least a factor of 5×10^3 with the aid of the MCP. This allows to provide such image brightness on the ICT screen that is necessary for reliable record of the ICT output image with the CCD readout unit. Image gain (a conversion coefficient) can be adjusted by changing a voltage on the MCP.

With the aid of an objective lens the visible image is transferred from the ICT screen to the TVC 4 CCD matrix, is readout, digitized and transmitted to PC system unit memory for subsequent processing and displaying. The TVC 4 is power-supplied from the PC.

Controlling electronics including PSU 3, SwPG 2_1 and ShPG 2_2 provides ICT operation in a static (continuous) or dynamic (pulsed, waiting) mode.

In a static mode of X-ray camera operation when MCP is supplied by DC voltage and TVC works in continuous mode, an object image coming to the ICT input is continuously displayed on the PC display. In dynamic mode the MCP is blanked if there is no pulse of camera triggering. Therefore, there is no image on the ICT screen. When a triggering pulse is applied to the CU, then the SwPG forms a linearly varying sweep voltage, the ShPG generates a rectangular pulse that unblanks the MCP for the time of a direct sweep pass and TVC records to the PC an image which was registered on the ICT screen. On completion of a direct sweep pass the MCP is blanked by the ShPG.

The camera complete set contains two changeable control units: CU-1 (fast) and CU-2 (slow). They my be triggered by electrical or optical pulses.

A mode of X-ray camera operation (either single-frame or streak) depends on whether the SwPG is disconnected with ICT deflection plates or is connected to them. In the first case a single-frame («FRAME») mode is realized; in the second case a streak («STREAK») mode is realized. In single-frame mode the frame duration is from ~10 ns up to ~660 µs. In streak mode the full sweep time is from 2 ns up to 600 µs.

The TVC has two modes of image record, namely continuous and waiting according to «STAT» and «DYN» modes of X-ray camera operation. In continuous mode the TVC reproduces on the display a constant or slowly changing image that is readout from the ICT screen. In waiting mode it records (according to a synch pulse coming from the X-ray camera) an image of the high-speed process to be recorded.

A photosensitive working area of changeable slit Au and CsJ photocathodes is a narrow strip with a 0.1 mm width and a length somewhat greater than 15 mm that in one case is deposited on a very thin substrate from nitrocellulose (parylene) and in the other case is deposited on a substrate from beryllium foil of a 15 µm thickness. Both substrates are transparent for soft X-ray. A photocathode-strip is vertically oriented. Only that part of the image that is projected on the photocathode is converted into an electron image that falls on the photosensitive strip.

A photosensitive working area of changeable frame Au and CsJ photocathodes on substrates from beryllium foil is a rectangle of a size not less than 6 mm x 12 mm.

A «TRIG OUT» output synch pulse of the X-ray camera that is used for TVC synchronization can also be used for triggering other external devices.

The camera is power-supplied from ac industrial mains with a (85 to 264) V voltage and a (50 to 60) Hz frequency. Options with input 12 or 24 VDC supplying mains are available for camera application in conditions of super high electrical interferences.

2.2. Construction and controls

There is a bellows (see fig. 1 and fig. 2) with a flange at the ICT input. With the aid of this flange the X-ray camera is vacuum-tightly jointed with a flange of an evacuated camera inside which a process accompanied by soft X-ray radiation will take place. This may be, for example, a process of powerful laser radiation interaction with a target. In this case the indicated evacuated camera is called a camera of interaction that has an output flange for jointing with the X-ray camera.

The X-ray camera with a fastening plate fastened to its base is set on a horizontal plane immediately adjacent to the output flange of the evacuated camera of interaction and is vacuum-tightly jointed with the flange of the ICT bellows with the aid of a centering steel and elastic sealing spacers as well as a special throwing on clamp (that are contained in the X-ray camera complete set).

Then an optical axis of the X-ray camera is turned in a horizontal plane in any direction by an angle ~10 degrees with respect to a direction of recorded radiation incidence on the ICT photocathode. The ICT bellows allows to do it. It is necessary because sufficiently hard X-ray radiation that as usually is present together with soft X-ray radiation may fall on the ICT MCP sensitive to hard X-ray radiation and may give rise to a false background on the image of a sweep of the process to be recorded. After that the camera is fastened with the aid of screws or wood screws passing through slots in the fastening plate and screwed in the plane where the camera is mounted.

When transporting the X-ray camera and when it is disconnected with the camera of interaction, the ICT bellows flange must always be hermetically closed with a technological end-cap that is pressed against the flange with the aid of the throwing on clamp mentioned above (the end-cap is also contained in the camera complete set).

With the aid of a special wrench-holder the photocathode can be set in or removed from the ICT through the bellows when the latter is disconnected with the camera of interaction. Two different test-objects representing so called "air" test-objects etched in copper foil covered with nickel may be set practically immediately adjacent to the photocathode with the aid of another wrench-holder. One of them is a frame test-object (fig. 3a) and the other is a slit test-object (fig. 3b). By irradiating the test-objects with continuous or pulsed soft X-ray or UV radiation (last for photocathode on parylene only) it is possible to check X-ray camera functioning and in this case to measure its spatial resolution in both static and dynamic modes when camera is operated in a single-frame and a streak mode.

Evacuation of the ICT till forevacuum as well as air leak-in to the atmospheric pressure must be done very slowly (it is usually made through a special device-a leak) in order not to damage by air flow a fragile super thin substrate with the photocathode. A working pressure of residual air at which a voltage may be applied to the ICT electrodes must be not worse (not higher) than 6 x 10^{-4} Pa. At a higher pressure electrical strength of interelectrode spaces may be less than working voltages and, as a result, the ICT photocathode may become disable because of breakdowns. If the X-ray camera will be used in the streak mode («STREAK») only for recording a time dependence (variation in time) of soft X-ray radiation intensity, then X-ray filters (foils of different metals) transmitting radiation in a required spectral range are set in the path of radiation propagation to the ICT photocathode.

If one needs to project on the photocathode an image of the object and to record a spatial-time picture of its "life" in streak or single-frame («FRAME») modes, in addition to the above-mentioned filters an obscure, i.e. a metallic plate (sometimes a lead plate for hard X-ray cut-off) which is non-transparent for soft X-ray radiation and has a small hole acting as a photographic lens is set at certain distances from the ICT photocathode and from the object (it is aligned with the object and the ICT photocathode center); a ratio of these distances defines a projection scale.

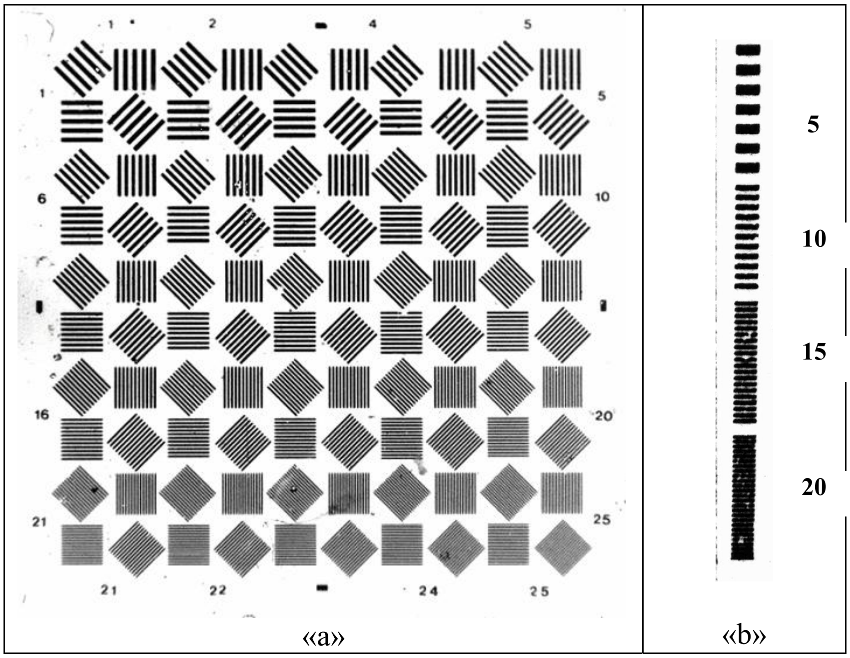


Fig. 3. The negative images of frame (a) and slit (b) test-objects. Figures near ranks of the slit test-object show the number of line pairs per millimeter (l.p./mm) in corresponding ranks; the number of l.p./mm in squares of the frame test-object is given in Table 1.

Table 1.

Square No.	1	2	3	4	5	6	7	8	9	10	11	12	13
Number of l.p./mm	6.3	6.5	7.0	7.4	8.0	8.4	9.0	9.4	10.0	10.5	11.0	12.0	12.5
Square No.	14	15	16	17	18	19	20	21	22	23	24	25	
Number of l.p./mm	13.0	14.0	15.0	16.0	17.0	18.0	19.0	20.0	21.0	22.0	24.0	25.0	

A diameter of the hole defines X-ray "relative aperture" of the obscure and spatial resolution provided by it. The above-mentioned parameters of the obscure contradict one another: the greater the hole's diameter the greater "relative aperture" and the lesser spatial resolution and vice versa.

An ICT compartment closed with a overhead housing cover is located on the horizontal plate in the upper part of the camera behind its front panel. This compartment contains the ICT placed in an electromagnetic shield.

The ICT bellows protrudes through a hole in the camera front panel.

The tube with TVC is fastened to a rear panel of the ICT compartment (fig. 4). In lower part of the camera the power supply unit and one of two changeable control units are located.

Fig. 4. K010X camera (view from TVC side).

2.3. Complete set

A typical camera complete set is presented in Table 2.

Table 2

No.	NAME	AMOUNT	NOTE
1	K010X camera, (without control units and CCD readout unit)	1	Contains PV-204XM ICT and power supply unit
2	Control unit CU-1 (fast)	1	
3	Control unit CU-2 (slow	1	
4	RU-05M CCD readout unit of digital image recording system	1	Complete set is given in RU-05M Documentation
5	Contrivances, spare parts and interchangeable parts:		
5.1	Mains power cable	1	
5.2	Coaxial cable	1	For camera triggering
5.3	Slit air test-object	1	For checking spatial resolution
5.4	Frame air test-object	1	For checking spatial resolution
5.5	Fixing plate	1	For camera fixing on the working place
5.6	Fuses 2A	2	
5.7	Key-holder: «Photocathode key» «Test-object key»	 1 1	For installation and replacement of: photocathodes only photocathodes with test-objects
5.8	Changeable photocathodes: -slit Au on parylene - slit CsJ on parylene -slit Au on beryllium - slit CsJ on beryllium - frame Au on beryllium - frame CsJ on beryllium	4 4 1 1 1 1	
5.9	Technological end-cap with centering and seal spacers	1	For hermetization of ICT input
5.10	Throwing on clamp	1	For jointing adapter branch pipe or technological end-cap with ICT bellows
6	K010X X-ray image converter camera Documentation	1	
7	Package	1	Case

3. CAMERA TUNING

After autonomous tuning of the power supply unit and control units the preliminary complex tuning of the camera was carried out with the application of time-analyzing ICT with S-20 photocathode. Its design and sensitivity its deflection plates was the same as for X-ray ICT of PV-204XM type. The L-05 Lighter [1] based on LED was used for tuning and check of the spatial resolution at all ranges in a streak mode and in a framing mode. This lighter was specially designed for control of serviceability of image converter cameras of nano-micro-millisecond range and for checking their spatial resolution. Its light pulse has variable duration from 30 ns to 1ms. The picosecond (50 ps) L-04 Lighter [2] based on LD was used with Stanford DG-535 generator of delayed pulses for sweep coefficient tuning and measuring of sweep coefficient nonuniformity and camera's jitter.

Then the ICT with S-20 photocathode was replaced with the X-ray PV-204XM ICT and final adjustment of potential of a PV-204XM focusing electrode was carried out only. For this the frame test-object (fig. 3a) irradiated by soft X-ray was set practically immediately adjacent to the photocathode.

4. TEST RESULTS

The camera was tested in Russia with the help of continuous and pulsed electron beam X-ray setup in static and dynamic modes with frame duration from 0.2 to 650 µs and a full sweep time from 0.2 to 600 µs when X-ray quantum energy was 8-12 keV. The intensity of an electron beam X-ray setup was not enough for test of the camera on more short ranges. The spatial resolution was from 5 l.p./mm for a short frame and sweep time up to 10 l.p./mm and even more for long ones (fig. 5 and fig. 6).

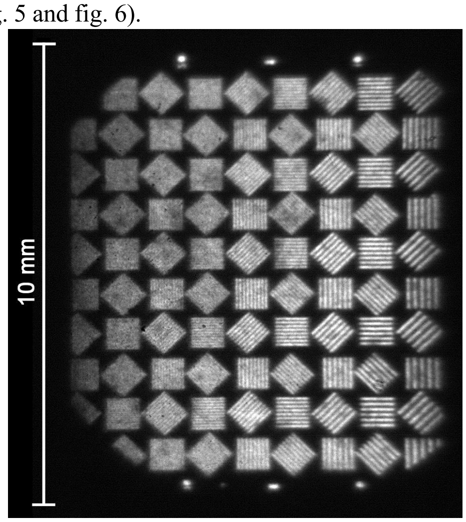


Fig. 5. The image of frame-test object when frame duration was 58 µs. The square with 12 p.l./mm one can see in the centre of image.

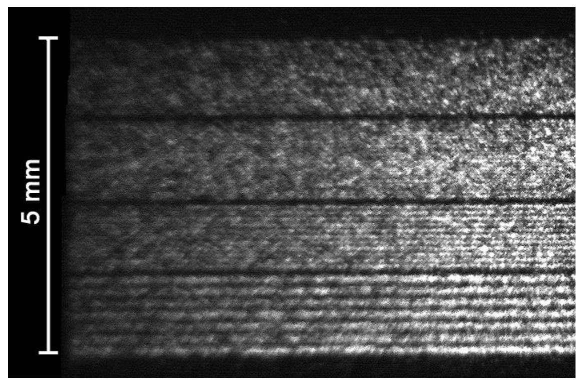


Fig. 6. The image of slit test-object sweep when sweep coefficient was 300 µs/cm (600 µs full sweep time). Two ranges with 5 and 10 p.l./mm one can see.

Then the tests of the camera was carried out in China with the help of UV nanosecond and femtosecond lasers. The tests results are presented below in **TEST REPORT**.

1. Measurement of the spatial resolution in single-frame mode with Au slit photocathode on parylene substrate**.**

A special slit air test-object (fig. 3b) was set practically immediately adjacent to the photocathode and was used for measurement of spatial resolution.

Result: spatial resolution was equal to 10 l.p./mm at all ranges; at the same time the maximum input density of energy of a pulsed UV laser (λ = 248 nm, 20 ns pulse half-width) on the photocathode of the image converter tube was 600 $\mu J/cm^2$ for the shortest range when frame duration was 11 ns.

2. Measurement of the dynamic range (DR) of CCD readout system and observe its functions.

DR was determined by using a traditional criterion as a ratio of the maximum signal corresponding to the maximum output ADC code to a root-mean-square deviation of a noise signal with CCD matrix fully closed from light at different values of CCD camera gain.

Results: DR =800, 2130 and 2460 when CCD Gain = 12 dB and, correspondently, 1 TV line, then 10, and then 100 TV lines are used for drawing profiles of relative image brightness (intensity).

DR = 315, 1020 and 2000 when CCD Gain = 24 dB and, correspondently, 1 TV line, then 10, and then 100 TV lines are used for drawing profiles of relative image brightness (intensity).

DR =90, 286 and 880 when CCD maximum Gain = 36 dB and, correspondently, 1 TV line, then 10, and then 100 TV lines are used for drawing profiles of relative image brightness (intensity).

Basic software of CCD readout system allows:

- to reproduce on the display a full recorded image or any part of it in the scale selected by the operator;
- to store a recorded image or a sequence of frames on PC hard and removable disks;
- to accumulate images on CCD matrix and in PC;
- to combine images (sum or difference of the latest image input and the recorded file; sum or difference of two files);
- to subtract regular noises (background);
- to rotate, about the frame center, the obtained image by the angle selected by the operator;
- to draw profiles of relative image brightness (intensity) in the chosen by the operator one or two horizontal (X) and one vertical (Y) sections; in so doing a section can be in the form of both a line and a window of an adjustable width;
- to measure a width of relative brightness profiles at the levels of 0.1 and 0.5 from their maximum as well as the intervals corresponding to a rise (or fall) of profiles between 0.1 and 0.9 (0.9 and 0.1) levels;
- to measure relative image brightness in the point or zone of intersection of horizontal and vertical sections with the possibility of extension of the brightness scale by a factor of 2, 5, and 10 or its compression by a factor of 1\16, 1\8, 1\4 and 1\2;
- to measure a velocity of the movement of typical image's parts in the mode of a linear sweep of the image;
- to draw on the image the lines of equal brightness (isophoto) at a level of brightness selected by the operator (from 0 to 255 or from 0 to 4095 for 8-bit and 12-bit regimes, respectively) or a family of these lines with a selected step of brightness variation;
- to carry out digital correction of the image (brightness, contrast, and gamma);
- to reproduce the image in grey (black-and-white), blue, and multi-colored (pseudo-coloring of equal-brightness zones) palettes;
- to inform the user about ADC overflow; in so doing, where over illumination takes place, a red color appears on the black-and-white image and on the image in blue palette whereas a white color appears on the image in multi-colored palette (option of over illumination indication on the black-and-white image and the image in blue palette can be switched on/off at the user's wish).

3. Measurement of frame durations and sweep coefficients with the help of pulsed UV laser (λ = 248 nm, 500 fs pulse half-width) and Stanford DG535 pulse generator.

The results of measurements are presented in Table 3.

Table 3

Range, ns/cm	Frame duration of control unit CU-1 ,ns, measured in: China / Russia	Sweep coefficient of control unit CU-1, ns/cm, measured in: China / Russia	Range, μs/cm	Sweep coefficient of control unit CU-2, μs/cm, measured in: China / Russia
1	11 / 11	1.0 / 1.0	0.1	0.102 / 0.1
3	16 / 16	3.04 / 3.0	0.3	0.316 / 0.3
10	37 / 37	10.0 / 10.0	1	1.04 / 1
30	80 / 80	30.0 / 30.0	3	3.15 / 3
100	280 / 254	101.6 / 100.0	10	10.4 / 10
			30	31.5 / 30
			100	105.0 / 100
			300	312.0 / 300

4. **Measurement of spatial resolution in streak mode** with Au slit photocathode on parylene substrate and with the help of a pulsed UV laser (λ = 248 nm, 20 ns pulse half-width).

Results: the spatial resolution on all the ranges of both control units is not less than 10 l.p./mm, except for a range of 1 ns/cm where spatial resolution is 5 l.p./mm.

5. Measurement of the dynamic range (DR) on 30 ns/cm range in streak mode with the help of a pulsed UV laser (λ = 248 nm, 20 ns pulse half-width).

DR was determined as a ratio of maximum recordable input signal to minimum recordable input signal.

Result: DR $\geq$ 200.

6. Measurement of the jitter by two ways.

Results: 1) value of the K0010X camera jitter measured by oscilloscope is ≤ 50 ps on the 1 ns/cm range;

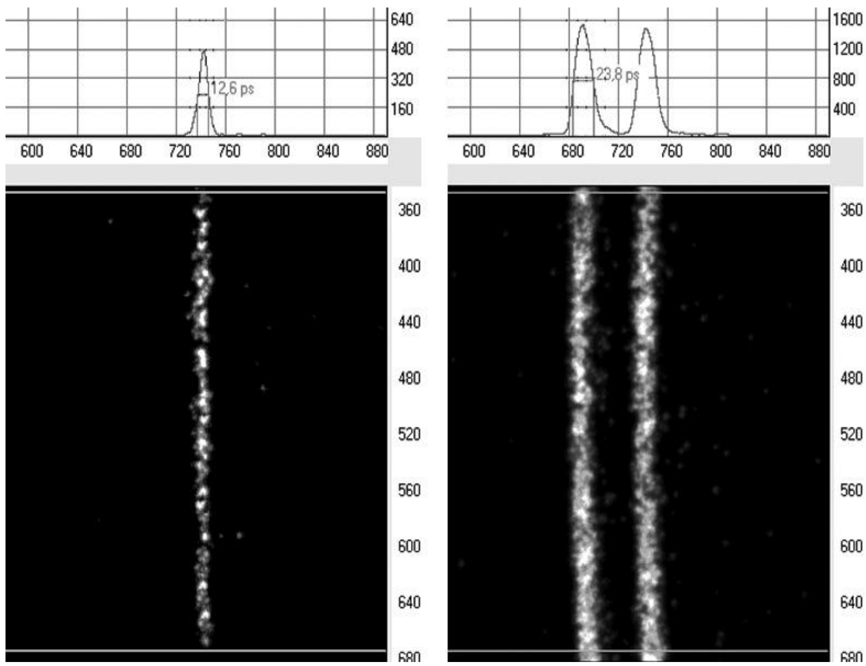
2) value of total jitter of the K010X camera + Stanford DG535 pulse generator measured with the help of a pulsed UV laser (λ = 248 nm, 500 fs pulse half-width) is 200 – 250 ps on the 1, 3 and 10 ns/cm ranges.

7. Measurement of temporal resolution with Au slit photocathode on parylene substrate in streak mode with the help of a pulsed UV laser (λ = 248 nm, 500 fs pulse half-width).

Temporal resolution was determined as a half-width of a recorded input laser pulse.

Results. Temporal resolution depends on a density of energy on the photocathode of the image converter tube. The greater the density the worse the temporal resolution. The minimum of measured temporal resolution (the best value) on 1 ns/cm range was 10.4 ps and average value of it under this conditions was 15.1 ps. When density was increased by a factor of 3.2 an average value of temporal resolution became 16.6 ps. When further this density was increased once more by a factor of 10 an average value of temporal resolution became 29.4 ps.

In fig. 7 two pulses (a and b) of a femtosecond UV laser recorded by the K010X camera are presented.



a b

Fig. 7. Two pulses (a and b) of a femtosecond UV laser recorded by the K010X camera: the density of energy on the photocathode of the image converter tube for the second double pulse (b) was by a factor 3.2 greater than for the first single pulse (a).

5. CONCLUSION

The miniature K010X soft X-ray streak and single frame camera is created as a result of design. Preliminary results of camera tests carried out in Russia and China showed its normal functioning and confirmed in common a compliance its main parameters to specification. The camera is not a complicated device, simple in controlling and is serviceable in operation. There is no problem with its transportation because it is easy gone into a small case.

At the next step of camera test such its main parameters as spatial and temporal resolution will be measured with the use of soft X-ray pulses produced by a powerful laser beam focused on a surface of a solid target.

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