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Technique for measuring basic characteristics of electron-optical cameras

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Abstract. **A procedure is described for determining the basic parameters of linear-sweep electron-optical cameras. The techniques are considered for measuring the limiting temporal resolution and dynamic range of the PS-1/S1 camera using a femtosecond laser and sinusoidal-modulated laser radiation.**

Keywords: *electron-optical camera, picosecond–femtosecond laser radiation, temporal resolution, dynamic range.*

1. Introduction

Electron-optical cameras (EOCs) with linear sweep (streak cameras) are widely used in laser physics, laser plasma diagnostics, semiconductor physics, accelerator technology, and other areas of experimental physics [1 – 4] since they allow direct temporal measurements of the processes under study. The accuracy of such quantitative measurements is stipulated by the specific values of the EOC engineering characteristics determined during the dynamic tests which are aimed at setting up the camera and preparing it for operation. The most important engineering characteristics of EOCs include, first and foremost, temporal resolution and dynamic range of recording. The determination of specific values of these parameters should be accompanied by an indication of the conditions under which the measurements have been conducted, namely, the radiation source characteristics, camera operation regime, method of recording the output image from the EOC screen, etc.

An important issue related to the use of EOC is the possibility of practical implementation of the camera's basic parameters specified in the passport. The aim of this work is to equip users with a practically convenient technique to allow them to measure these parameters independently and also to maximise the use of the camera's engineering characteristics during experiments.

The work describes a technique for determining the above-mentioned EOC engineering characteristics using the example of a PS-1/S1 streak camera equipped with an electron-optical image converter tube (ICT) of the PIF-01 type. The PS-1/S1 camera is designed and currently manufactured at the facilities of the GPI Photoelectronics Department, RAS. The results of measurements of the limiting temporal resolution and recording dynamic range (DR) of this camera are presented.

2. Temporal resolution and instrumental function

In general case, temporal resolution characterises the capability of the device to separately record events following each other at certain time intervals. For a streak camera, temporal resolution is understood as the camera's capability of distinguishing between two events corresponding to two close consecutive time moments. In practice, the streak camera's temporal resolution is determined by the degree of instrumental distortions introduced both by the camera itself and the recording device, and also by the method of post-processing of the recorded images. To describe the distortions peculiar to the EOC, the concept of the temporal instrumental function (TIF) is introduced, which is defined as the camera response to an optical input pulse of infinitely short duration (δ pulse) and represents a versatile characteristic of the device. The module of the TIF's Fourier transform (modulation transfer function) calculated at a particular contrast value specifies the temporal resolution of the device.

For the practical measurement of the EOC temporal resolution in accordance with the definition given above, a method of two δ pulses is often used. Two δ pulses of comparable intensity are fed to the camera's entrance slit. These pulses can be obtained, for example, by reflecting a single pulse from two surfaces of a glass plate. As the time delay between the pulses decreases, the modulation factor characterising the depth of the dip in the recorded intensity distribution also decreases.

The description of temporal characteristics of ICTs and streak cameras in terms of TIF was first proposed in 1969 [5]. However, the practical difficulties of direct measurement of the instrumental function at that time and the lack of a generally accepted criterion for evaluating the relationship between TIF and temporal resolution led to the fact that different authors invested their own meaning to the concept of temporal resolution of the ICT and electron-optical camera. Therefore, when considering devices with comparable temporal resolution, it was necessary to take into account how this temporal resolution was determined and, in particular, what the minimum value of the modulation coefficient was that could be considered legitimate for its evaluation.

With the rapid development of laser technology, and also with the advent of femtosecond lasers and laser pulse compression techniques, direct measurement of temporal resolution and TIF in modern streak cameras, which usually have a

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limiting temporal resolution of about 1ps, turned out not complicated. However, the problem of unambiguous determination of temporal resolution remained, since a single criterion for assessing the EOC time resolution was not established. In our works [6, 7], it was proposed to use the TIF half-width (FWHM) as such a criterion, which seems convenient when comparing the temporal parameters of various cameras and image converters.

As an example demonstrating the quantitative relationship between TIF and temporal resolution (two δ pulses), we give the following numerical estimates. Let us represent the modulation coefficient, which determines the depth of the dip between the pulses, in the form

$$M = [(I_{\max} - I_{\min})/(I_{\max} + I_{\min})]\times 100\%,$$

where $I_{\max}$ and $I_{\min}$ are the maximum and minimum intensities in the resulting distribution. For further evaluations based on the experiments performed, we accept the delay Δt corresponding to $M = 20\%$ as the minimum time delay between the pulses. As TIF, we consider several time-dependent functions $A(t)$ with the same half-width τ, but various shapes.

In particular, in the case of a Gaussian form of TIF

$$A(t) = \exp[-4\ln 2(t^2/\tau^2)],\ \Delta t = 1.25\tau.$$

For triangular TIF

$$A(t) = \begin{cases} 1 - |t|/\tau & \text{for } |t| \leqslant \tau, \\ 0 & \text{for } |t| > \tau, \end{cases} \quad \Delta t = 1.33\tau.$$

In the case when TIF has a dispersion form

$$A(t) = 1/(t^2 + \tau^2/4),\ \Delta t = 1.28\tau.$$

At $M = 15\%$, Δt is 1.19τ for the Gaussian form of the instrumental function, 1.26τ for the triangular form, and 1.16τ for the dispersion form, while $\Delta t = 1.11\tau$, 1.18τ, and 1.02τ at $M = 10\%$, respectively.

It is seen that the temporal resolution Δt varies depending on the accepted value of the modulation coefficient M and the TIF shape, which leads to some uncertainty in the evaluation of the true temporal resolution of the device. As for the TIF, its half-width τ is determined accurately and is close to the Δt value measured by the classical method of two δ pulses with the coefficient $M = 10\%-20\%$.

Yet another way to determine the EOC's TIF is based on the use of sinusoidal-modulated laser radiation (SMLR), the time modulation profile of which is known in advance. A remarkable property of such radiation is as follows: if the temporal distribution of the input signal intensity being analysed by a linear temporal detector has a sinusoidal profile with a given frequency, then the output distribution has a profile of the same shape with the same frequency, but, generally speaking, with different amplitude and phase.

It should be noted that if the test radiation intensity is described by the function $I(t)$ with a known shape and duration (or modulation) comparable to the half-width of the EOC's TIF, the true shape of the TIF can be determined from the convolution relation

$$B(x) = \int I(t)A(t,x)\,\mathrm{d}t, \tag{1}$$

where $B(x)$ is the glow intensity of the EOC screen; x is the coordinate along the sweep direction; and $A(t, x)$ is the camera's TIF in the linear sweep regime. However, as a rule, the solution of such an equation is a rather complicated task, which can be substantially simplified if the temporal waveforms of the input pulse and instrumental function are known in advance.

To fully determine the TIF in the case of its measurement using the input test pulse with a known duration t_0, it is also necessary to know the duration t_{reg} of the registered image of this pulse. In particular, when both the input pulse and the TIF are Gaussian, the half-width of the instrumental function can be calculated from the relation $t_{\text{reg}}^2 = t_0^2 + \tau^2$ that follows from (1).

In determining the TIF by means of SMLR in the case of a Gaussian waveform of the EOC instrumental function, as a result of solving Eqn (1), we obtain a simple formula to calculate the half-width τ:

$$M = M_{\text{in}}\exp[-\pi^2\tau^2/(4\ln 2\cdot T_{\text{mod}}^2)], \tag{2}$$

where M_{in} is the coefficient of radiation modulation at the camera input; and T_{mod} is the modulation period.

The results of experiments [6, 7] to determine the EOC temporal resolution by the two methods virtually coincide, and so the choice of the method only depends on the specific experimental conditions.

It should be noted that the instrumental function and temporal resolution defined above depend on the input signal intensity. However, assuming that the measurements are conducted under the condition of EOC operation in the linear recording regime, when the input and output signals are still proportional, the values of these parameters do not depend on the input intensity.

The EOC capability of recording temporal processes with a limiting temporal resolution is largely determined by its instrumental function. Therefore, it is proposed to use the TIF half-width as a criterion characterising the camera capability of distinguishing events being close in time and to consider this value as the limiting temporal resolution of the corresponding EOC.

3. Dynamic recording range

Another important EOC characteristic is the transfer characteristic, the linear part of which determines the DR of the camera recording. Besides the dependence of the measured pulse duration on the camera's TIF, its difference from the input pulse duration is also caused by the spread in initial velocities of photoelectrons and the impact of Coulomb interaction that occurs in the streak tube on the electron bunch path from the photocathode to the luminescent screen. Numerical calculations show [8] that, in a streak tube with axial symmetry, in particular, in the PIF-01 streak tube, besides the Coulomb broadening experienced by the electron bunch near the photocathode, an additional Coulomb broadening of the electron bunch arises near the crossover point, where the bunch cross section is minimal. Depending on the Coulomb interaction intensity, the pulse duration can be measured on the linear or nonlinear part of the transfer characteristic. In the nonlinear region, a noticeable temporal broadening of the measured pulse is observed as the input radiation intensity increases.

Based on this, in [9], the DR definition for streak cameras, which assumes its measurement by means of a laser pulse of known duration, was given and has become afterwards generally accepted. According to this definition, the DR is the ratio $I'_{\max}/I'_{\min}$, where $I'_{\min}$ is the minimum input pulse intensity at which the pulse duration can be still reliably measured against the background noise; and $I'_{\max}$ is the input pulse intensity at which the measured output pulse duration becomes 20% greater than the input one. It is obvious that the DR of the system of image recording from the EOC screen should exceed the DR of the camera under study.

The DR determination in streak cameras is conducted in relation to each particular sweep system using either a laser pulse of extremely short duration (δ pulse) or a longer laser pulse corresponding to the time scale of the sweep system under consideration. In the first case, the camera's TIF is measured, the image of which recorded on the EOC screen in the direction perpendicular to the sweep direction corresponds to a single resolvable element characterising both temporal resolution and dynamic spatial resolution of the streak camera. For example, for the PS-1/S1 camera operating on the linear part of the DR in the fastest sweep regime, typical values of temporal and spatial parameters of the resolvable element are ~1 ps and ~100 μm, respectively. Under these conditions, the upper boundary of the linear part of the DR is determined by the temporal (spatial) broadening by 20% of a single resolvable element.

However, if the input laser pulse duration exceeds the characteristic TIF width, the swept image can be considered as consisting of several resolvable elements. An increase in the input intensity leads to an increase in the number of photoelectrons inside each resolvable element. When the input pulse intensity reaches the maximum value $I'_{\max}$ for a single resolvable element (in the δ pulse regime), each resolvable element experiences a 20% broadening; however only two external elements contribute to the overall broadening of the pulse recorded. For the actual input pulse duration, this broadening is less than 20%, which allows an additional increase in the input radiation intensity up to its upper boundary $I'_{\max}$, at which a 20% increase in the measured output pulse duration is realised [10].

One of the experimental methods for DR determination is that a sequence of pulses obtained as a result of multiple reflections of initial laser pulse inside, for example, the Fabry–Perot reference is fed to the EOC input slit. With a known reflection coefficient of the reference mirrors, a sequence of radiation pulses with decreasing intensity at a given and fixed attenuation coefficient is formed. By counting the number of pulses recorded on the camera screen with intensities from maximum to minimum, found in accordance with the above criterion of 20% broadening, it is possible to determine the DR by the formula $I'_{\max}/I'_{\min} = 1/(R_1R_2)^{n-1}$, where R_1 and R_2 are reflection coefficients of the reference mirrors; and n is the number of pulses. If the input radiation intensity is chosen correctly, it is possible to record a sequence of pulses during a single laser flash, which is an obvious advantage of this method.

Another way for DR determination is the use of calibrated neutral filters installed in front of the EOC entrance slit. In this case, the measurement time increases because at least n laser flashes are required to record the radiation pulses with intensities in the range $I'_{\min} - I'_{\max}$. This number increases if, in order to increase the measurement accuracy of the corresponding intensities, it is necessary to average them over the number of laser flashes.

We should note that the DR can be measured by means of SMLR. In the linear part of the DR, an increase in the radiation intensity with a previously known modulation period should not result in a change in the modulation depth. When switching to the nonlinear DR region, the modulation depth decreases with increasing intensity. In this case it is also possible to introduce a quantitative criterion ($I'_{\max}/I'_{\min}$) for DR determination using SMLR, if $I'_{\min}$ is considered as the minimum input radiation intensity with a 100% modulation depth and a known period, provided these parameters can be reliably measured against the background noises. As for the $I'_{\max}$ value, this intensity requires the determination of the minimum modulation depth, which we will consider as a limiting one. It is obvious that, as in the case of DR measurement by means of a pulse, the DR value depends on the modulation period if SMLR is used.

4. Measurement procedure

Experimental measurements of the main characteristics of the PS-1/S1 EOC (Fig. 1) with the PIF-01 image converter tube were performed using a commercial Ti:sapphire laser (Tsunami, Spectra-Physics, USA), which emitted a sequence of pulses with a duration of ~30 fs and a repetition rate of ~75 MHz at a wavelength of $\lambda = 800$ nm [11]. The camera contained an input optical system consisting of two Helios-44 lenses displaying the input slit onto the photocathode, and C8484-05G (Hamamatsu, Japan) or ANIMAPX-25 (Optronis, Germany) readout systems. In the first case, the camera's output screen was projected by means of a lens onto the CCD matrix with the image magnification factor selected in accordance with specific experimental conditions. In the second case, the readout system was in optical contact with the camera's output screen (Fig. 1). If necessary, a single pulse with an energy of several nanojoules could be separated with the use of the electro-optical Pockels cell. A fraction of laser radiation was diverted to the frequency divider consisting of a photodiode and an electronic unit forming a synchronisation pulse. This pulse was fed to a delay generator, which controlled the EOC launch, the readout system and the Pockels cell.

To determine the EOC's TIF, it is necessary, as mentioned above, that the test laser pulse should be much shorter than the assumed maximum temporal resolution of the camera. In

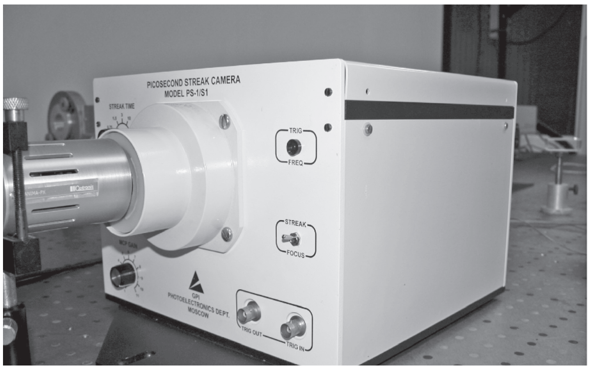


Figure 1. General view of the PS-1/S1 camera.

our case, this condition is satisfied: the pulse duration is 30 fs and the resolution is 1 ps. However, in the course of laser pulse propagation through the imaging input optics, its temporal broadening occurs, which leads to an increase in the pulse duration to a value comparable with the TIF width or even higher.

As is known, the duration of a transform-limited laser pulse passing through an optical medium can be calculated by the formula

$$t_{\rm out} = t_{\rm in}[1 + 7.68(D_{\omega}L/t_{\rm in}^2)^2]^{1/2}, \qquad (3)$$

where $t_{\rm in}$ and $t_{\rm out}$ are the durations of input and output laser pulses; D_{ω} (in fs^2 cm^{-1}) is the material dispersion of medium elements for a given laser wavelength; and L (in cm) is the length of the corresponding optical element.

Experimental measurement of the laser pulse duration at $t_{\rm in} = 30$ fs and $\lambda = 800$ nm, performed by means of an autocorrelator, has given a duration of about 800 fs for the output pulse passing through two Helios-44 lenses, which coincides with the pulse duration calculated by formula (3). Taking into account other glass optical elements (beam splitters, neutral filters, etc.) located on the radiation path from the laser to the EOC cathode, one can be expect that the pulse broadening should exceed 1 ps. In view of this, the EOC's TIF was measured by an input optical system incorporating a single thin cylindrical lens to form a slit image of the laser beam on the camera photocathode. All the features described should be taken into account in the DR determination. It should be emphasised that the measurements of the limiting temporal resolution and dynamic range in the PS-1/S1 EOC utilised a central part (10–15 mm) of the camera's output screen with a diameter of 25 mm, which has no strong image distortions caused by the aberrations of the ICT electron-optical system.

Before the TIF measurements, it is necessary to calibrate the camera sweep speed. In our case, such a calibration is carried out by measuring the time shift between two pulses formed either by the laser pulse reflected from two surfaces of a glass substrate or by spatial splitting of the laser beam, one part of which passes through the glass plate while the other propagates through the air. In both cases, the time delay between these two pulses is determined by the glass thickness and its grade. As a result, a spatiotemporal scale of ps pixel^{-1} is displayed on the readout device (the size of the CCD matrix element).

Since 2009, more than twenty PS-1/S1 EOCs have been tested at the laser facility of Photoelectronics Department of Prokhorov General Physics Institute, RAS, which slightly differ from each other both in the PIF-01 streak tube design and electrical control circuits. The results of these dynamic tests allowed us to determine the average TIF temporal range which amounted to 1–2 ps. The best temporal resolution obtained for several cameras was shown to be 0.8 ± 0.1 ps. Figure 2 displays a photograph of two pulses with FWHM less than 0.8 ps, recorded on the camera screen, and their microphotogram. The pulses are obtained by reflection of a single pulse from a glass substrate with a thickness of 1 mm. In this experiment, the sweep speed was equal to $\sim 1.5 \times 10^{10}$ cm s^{-1} (170 ps on a screen diameter of 25 mm) with a DR of about 8.

The use of SMLR for dynamic tests of the EOC is stipulated not only by the possibility of implementing another method for TIF determination, but also by the possibility of comparing the camera responses both to a single δ pulse and to fairly long radiation with a fine temporal structure. In work [6], quantitative measurements of EOC temporal characteristics were conducted for the first time by these two methods (by means of SMLR and a single pulse) in the picosecond range. For further continuation of such experiments, it was necessary first of all to develop sufficiently stable SMLR sources.

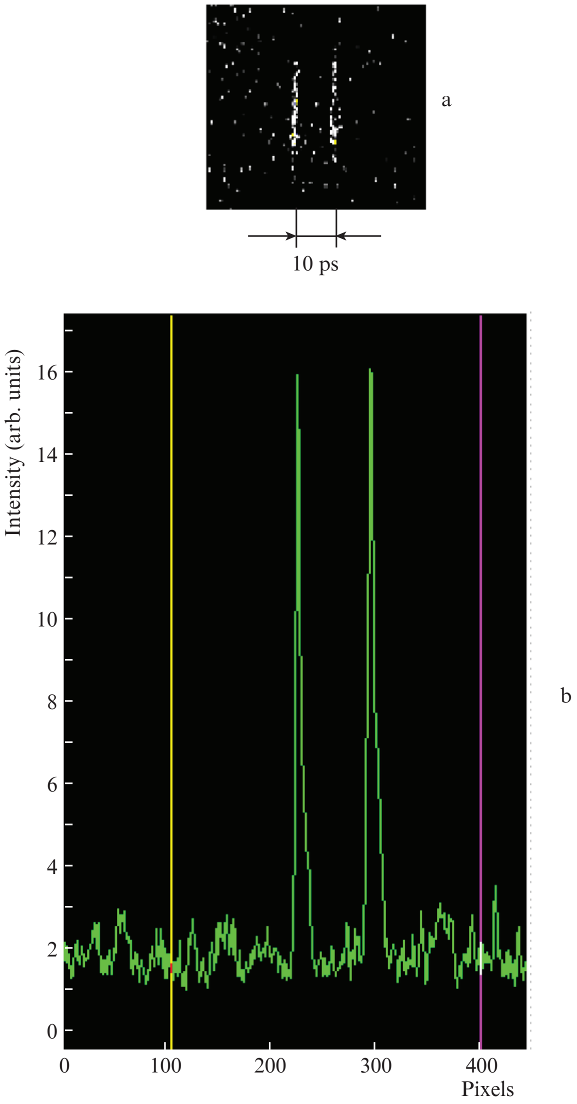


Figure 2. (a) Photograph of two laser pulses obtained by reflecting a single pulse from a glass substrate with a thickness of 1 mm, and (b) their microphotogram. The sweep speed is 1.5×10^{10} cm s^{-1}, and the scale is 0.13 ps pixel^{-1}.

One of the possible ways to obtain SMLR in the optical range is the use of a two-frequency laser generating two axial modes (regime of mode beatings) [12]. A smooth change in the spectral interval between these modes makes it possible to obtain output radiation with various temporal modulation profiles, that is, with various beat periods. In this case, the beat period is inversely proportional to the frequency gap between the modes. If the laser operates in pulsed regime, both modes are emitted simultaneously.

Another approach to solving the problem of SMLR generation is based on the use of frequency modulation of the carrier frequency of a laser pulse [13]. Initial radiation of a Ti:sapphire laser, representing a regular continuous sequence of femtosecond pulses is transmitted through a fibre or a lattice expander (stretcher). As the pulses pass through the stretcher, they experience temporal broadening, the value of which depends on the properties of the fibre waveguide or the dispersion of the diffraction grating, and acquire a close-to-linear frequency modulation (chirped pulses). The thus converted radiation is directed to a Michelson interferometer, where it is divided into two beams of equal intensity. The predetermined difference in the interferometer arm lengths determines the time delay between the beams at the output and thus sets the modulation period. By changing this difference, it is possible to obtain SMLR with various modulation periods.

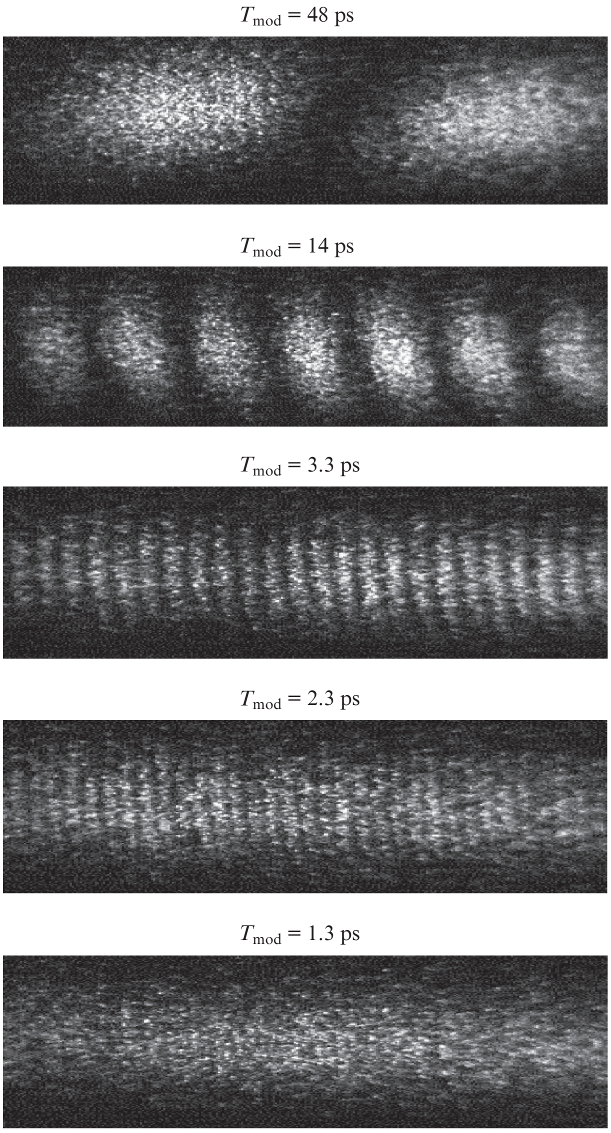
Both methods of SMLR generation were used to measure the TIF of an 'Imacon-500' streak camera [12, 13]. In these works, it was shown that in the picosecond range there is no significant difference in the results of EOC testing by means of a single pulse or SMLR.

In subsequent experiments, the PS-1/S1 camera was tested on a laser system consisting of a Tsunami oscillator and a regenerative TSA amplifier operating on the basis of the chirped-pulse amplification method. After amplification, a single pulse with almost linear frequency modulation was fed into the Michelson interferometer, at the output of which a streak camera was installed to record the total radiation. Figure 3 shows photographs of SMLR intensity profiles with various modulation periods. The TIF half-widths for this EOC, measured by the direct method, and also calculated by formula (2), turned out equal to 1.3 ps at a sweep rate of 1.25×10^{10} cm s^{-1}.

The DR recording measurements for PS-1/S1 cameras by means of a δ pulse at maximum sweep speeds have shown that its value does not exceed 10. As noted above, the DR value depends on the test pulse duration. In our work [10], the DR value was $\sim$22 at a laser pulse duration of 22 ps, which is twice the range obtained by testing with a laser pulse having a duration of 30 fs. Thus, the DR measured by a pulse, the duration of which exceeds the TIF half-width of the test camera, is greater than that obtained by the δ pulse. This fact must be taken into account in EOC certification by means of indicating in the specification the pulse duration at which the DR measurements have been actually performed.

To increase the EOC's DR, it is necessary to minimise the magnitude of electron beam broadening inside the streak tube, which occurs due to the Coulomb interaction of electrons near the photocathode and at the point of crossover. This can be done by reducing the input radiation intensity; in this case, the image intensity on the readout device should remain the same to satisfy the conditions for reliable measurement of the recorded pulse's half-width. To do this, it is necessary to reduce the useful signal loss arising on the electron bunch path from the camera's output screen to the CCD matrix.

At our EOC dynamic test facility (see Fig. 1), image transfer from the camera screen to the CCD matrix is performed by a lens, which results in light losses. We conducted experiments in two configurations: the PS-1/S1 EOC coupled with a C8484-05G readout system equipped with a lens to transmit the image from the screen with a demagnification of 2, and an EOC coupled with an ANIMAPX-25 CCD readout system which was in optical contact with the camera's output screen through a fibre-optic focon having a display ratio of 25 mm/12.5 mm. The pixel size of both matrices was 6.45 μm. The results obtained have shown that, in the first case, the DR measured by means of a laser pulse with duration of 30 fs was equal to $\sim$10, while in the second case under the same conditions it was 25.



$T_{\rm mod} = 48$ ps

$T_{\rm mod} = 14$ ps

$T_{\rm mod} = 3.3$ ps

$T_{\rm mod} = 2.3$ ps

$T_{\rm mod} = 1.3$ ps

Figure 3. Photographs of the SMLR intensity profiles with various modulation periods $T_{\rm mod}$. The sweep speed is 1.25×10^{10} cm s^{-1}. The central part ($\sim$10 mm) of the EOC's output screen is displayed.

5. Conclusions

The present paper describes a technique for measuring the basic characteristics of the PS-1/S1 EOC, namely, the limiting temporal resolution and DR recording. The above procedure offers an opportunity for users to independently measure these parameters provided that the appropriate laser equipment is available. The choice of the PS-1/S1 EOC is fully justified, since the laboratories of many scientific centres of Russia, such as LPI RAS, IRE RAS, INP SB RAS, and others, are equipped with that streak camera.

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