Quantum Electronics **37** (10) 927 – 933 (2007)

PACS numbers: 42.79.Ls; 42.55. –f
DOI: 10.1070/QE2007v037n10ABEH013665

Image-converter tubes for lasers and lasers for image-converter tubes (operating experience of the Photoelectronics Department, GPI, RAS)

M.Ya. Schelev

***Abstract*.** **Work in the field of electron – optical diagnostics of laser-induced rapid processes performed for almost half a century at the Photoelectronics Department at the General Physics Institute, RAS, is summed up. New femtosecond image-converter tubes have been developed, which provide the time resolution no worse than 100 fs in the slit scan (streak) regime, and photoelectron guns have been built for time-resolved studies of electron diffraction. The results of recent studies on manifold (up to fifty-fold) compression of picosecond electron bunches in nonstationary focusing fields are demonstrated.**

Keywords: *pico – femtosecond laser physics, time-analysing image-converter tubes and streak cameras, photoelectron guns for time-resolved studies of electron diffraction.*

1. Introduction

Today, as more than fifty years ago, when they were invented, time-analysing image-converter tubes (ICTs) are the only instruments allowing the direct observation of the development of individual phases of low-intensity optical emission processes in the time interval from 10 ps to 10 fs. A time-analysing ICT (Fig. 1) operates in the following way: the optical image of rapid processes focused on a photocathode is transformed to a photoelectron analogue in the form of a beam of accelerated electrons, which is focused by an electromagnetic lens and is visualised on the output screen (phosphor or an electron-sensitive CCD array). Simultaneously with the formation of the photoelectron image, the spatiotemporal transformation (deflection, shuttering, etc.) of the image is performed on the output phosphor screen with the help of rapidly changing electric fields. The time-resolved photoelectron image transformed to its optical analogue on the output screen represents the one- or two-dimensional picture of individual temporal phases of rapid process under study.

The idea of a time-analysing ICT that simultaneously focuses and analyses in time the image of rapid processes (streak imaging tube) was patented at the late 1940s by a known American researcher of the Australian origin J. Courtney-Pratt who was working in Great Britain at that time [1]. The physical foundations of the electron – optical photography with the theoretically substantiated time resolution limit of 10 fs was developed in our country in the early 1950s in papers of Zavoisky and Fanchenko [2]. On the initiative of scientists at the Kurhatov Institute of Atomic Energy, a group of researchers in the field of electrovacuum instrument making headed by Butslov at the Research Institute of Applied Physics (now Orion Research and Production Association) developed for the first time multi-cascade time-analysing PIM-UMI ICTs for detecting individual photoelectrons [3]. These devices, which never have been later reproduced by anybody anywhere in the world, provided the time resolution better than 10 ps in experiments on detecting extremely miniature spark discharges (IAE, 1953) [4] and in the studies of the physics of laser radiation (Lebedev Physics Institute, USSR Academy of Sciences, 1965) [5].

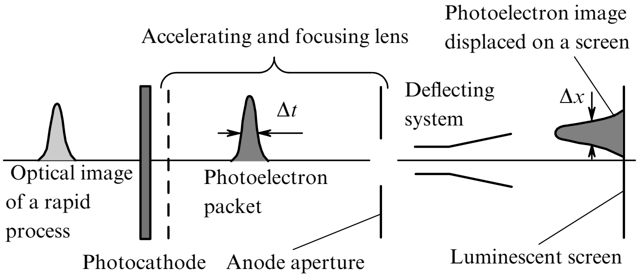


Figure 1. Spatiotemporal image conversion in a time-analysing ICT.

Scientists and specialists at the All-Russian Research Institute of Optical and Physical Measurements have made a great contribution to the development and production of time-analysing ICTs and streak cameras and to their applications in scientific studies, in particular, in quantum electronics. Works on the electron – optical instrument making have been headed at this institute by B.M. Stepanov from the mid-1960s and are being successfully continued at present. Around this time, Yu.E. Nesterikhin began to develop, first at the Institute of Nuclear Physics, Siberian Branch, USSR Academy of Sciences and then at the Institute of Automation and Electrometry, USSR Academy of Sciences, original time-analysing ICTs, which were later used in streak cameras. Wide experience in their applications in laser physics, high-current electronics, and plasma physics has been accumulated. A series of industrial streak cameras based on the developments of M.I. Pergament

---

M.Ya. Schelev A.M. Prokhorov General Physics Institute, Russian Academy of Sciences, ul. Vavilova 38, 119991 Moscow, Russia;
e-mail: m.schelev@ran.gpi.ru

Received 9 July 2007
Kvantovaya Elektronika **37** (10) 927 – 933 (2007)
Translated by M.N. Sapozhnikov

(IAE) and using domestic time-analysing ICTs has been produced at the Plant of Electronic Microscopes (Sumy town, Ukraine). High-speed streak cameras have been actively developed at the State Optical Institute, the Research Institute for Pulsed Technique, the Institute of Earth Physics, and the All-Union Electrical Engineering Institute. Thus, the Russian scientific school has become the ancestor of an entirely new scientific direction in technical physics, which is known now as high-speed image-tube photography.

The positive effect of using ICTs in science and technology has proved to be so significant that the studies devoted to the development of electron – optical methods and instruments stand out now as the independent direction of investigations in all industrially developed countries around the world.

Image-converter tubes combine remarkable properties, allowing, for example, the recording of spatial pictures of rapid processes containing $10^3 - 10^8$ elements of size 10 – 30 μm in a very broad spectral range (1 – 1600 nm) and up to 3 μm in the multiphoton photoeffect regime. The maximum quantum efficiency in some spectral regions can achieve a few tens of percent. Image intensifiers with gains $10^3 - 10^6$ provide the detection of single photons in each image element. This means that the image of an object with spatially-resolved elements emitting only a few photons can be obtained in the limit. The dynamic range of intensity detection in the single-photon photoeffect regime achieves $10^3 - 10^6$. Taking into account the fast response of the external photoeffect and the inertialless deflection of an electron beam in an external electric field, the time resolution can achieve $10^{-18} - 10^{-20}$ s in the limit; it is determined by the de Broglie wavelength of photoelectrons involved in imaging (which is less than 10^{-2} nm for 20 – 30-keV electron beams). In addition, electron – optical devices are readily compatible with computers and, thus, all these advantages make their development very promising for experimental studies of rapid processes.

2. Laser-oriented electron – optical diagnostics

Alexander Mikhailovich Prokhorov was the first to understand the outlook for applications of high-speed electron – optical diagnostics in laser studies. Owing to his great erudition and scientific anticipation, he concluded that ICTs can be used for the picosecond time-resolved recording of images of individual phases of laser-induced rapid processes. By his initiative and support, the first picosecond streak cameras were fabricated at the Lebedev Physics Institute in the early 1960s and the methods of their application in laser experiments were developed [6]. The record time resolution of ICTs in those years was no better than 10 ps, which, however, did not prevent to observe a number of phenomena that could not be detected by other methods. These are the experimental detection of moving foci upon self-focusing of laser radiation in nonlinear media, the observation of propagation of the ionisation front of a laser spark by successive breakdowns, the study of a fine temporal structure in the radiation of mode-locked neodymium glass lasers, measurements of the frequency shift of a single picosecond laser pulse and the time delay of picosecond laser pulses propagating in optical fibres [7]. The examples of recent applications of laser-oriented high-speed electron – optical diagnostics for studying rapid processes are experiments performed by our Department with groups headed by S.V. Garnov, E.M. Dianov, V.I. Konov, and I.A. Shcherbakov.

Thus, a picosecond streak camera was used in experimental studies of the dynamics of formation and development of femtosecond laser microplasmas in gases [8]. This camera operates in a broad spectral range (300 – 1100 nm), has a high spectral sensitivity of the input photocathode (2.1 mA W^{-1} at a wavelength of 800 nm), a sufficient dynamic range (no less than 10), and the time resolution no worse than 2.4 ps. The electron – optical method for spectral – temporal recording of plasmas was used for picosecond time-resolved investigations of the dynamics of formation and development of a spectral continuum and spectral lines of femtosecond laser plasmas in gases (air, argon, nitrogen, and helium). In these experiments, the generation of the second (even) harmonic of femtosecond laser pulses in subcritical-density plasmas was detected for the first time.

The detonation-like destruction of optical fibres caused by intense laser radiation was recorded photographically with a nanosecond streak camera operating in the slit scan (streak) regime [9]. The magnified image of the core of an optical fibre of diameter a few microns was projected on the entrance slit of the camera used for measuring the propagation velocity of an optical discharge. As a result, a 'rapid' detonation-like propagation of the optical discharge at velocities up to 3 km s^{-1} was observed in a silica fibre for the laser radiation intensity in the fibre core up to 40 W μm^{-2}.

A picosecond slit-scan streak camera was used to record radiation of lasers based on new active elements grown at the GPI, RAS. The operation of diode-pumped mode-locked solid-state lasers was studied. Lasers based on mixed $Nd:Gd_{0.7}Y_{0.3}VO_4$ vanadate crystals operating in different mode-locking regimes were fabricated. The best results were obtained in the case of passive mode locking produced by the Kerr nonlinearity. The laser pulse duration measured with a streak camera in this regime was 1.7 ps for the average output power of a few hundreds milliwatts.

3. Specialised lasers for ICT calibration

By introducing a noticeable contribution to the study of lasers and the interaction of laser radiation with matter, high-speed photoelectronics needed improvement, which required the development of specialised lasers. Therefore, one of the traditional directions of the research performed in the Department was the development of lasers generating ultrashort pulses with known parameters for calibration of ICTs. We have developed neodymium glass lasers generating only two modes with a controllable spectral interval between them [10]. Due to the mode beating, the initial radiation is modulated with a period from a few hundreds femtoseconds to a few picoseconds. The beat period and modulation depth are determined beforehand from spectral measurements. The method of mode beats provided the accurate calibration of streak speeds and precise measurements of the time resolution of ICTs operating in the regime of a linear (in time) scan of images of rapid processes restricted by a narrow slit (in the streak regime). A hybrid mode-locked Nd : YAP laser with a passive intracavity feedback based on a GaAs crystal was fabricated for the pulsed calibration of ICTs [11]. The laser emitted trains of pulses that were highly stable in energy (±1.5 %) and duration (4.5 ± 0.5 ps), and was used to pump F_2^- : LiF colour centre laser emitting pulses of duration less than 0.5 ps and to pump a fibre compressor emitting ~ 100-fs pulses.

At the Photoelectronics Department at the GPI, RAS, a Ti : sapphire laser emitting trains of 60-fs pulses at a pulse repetition rate of 82 MHz has been used beginning from 1995. A complete femtosecond Ti : sapphire laser setup includes a Ti : sapphire regenerative amplifier and second- and fourth-harmonic generators based on KDP and BBO crystals, respectively. Also, a BBO travelling wave parametric generator is used. Recently, a Ti : sapphire laser emitting highly stable single 30-fs pulses at 800 nm was fabricated. A laser that will emit single 10-fs pulses is being developed. Such lasers are needed for measuring the limiting parameters (time resolution, dynamic range, sensitivity, etc.) of experimental samples of vacuum devices developed and fabricated at the Photoelectronics Department.

4. Physics of photoemission and photocathodes

As lasers are developed, the requirements imposed on the parameters of electron – optical instruments more and more increase. This concerns the improvement of the time and spatial resolutions, the extension of the spectral sensitivity range, the reduction of the delay time and instabilities, the increase in the dynamic detection range, and the optimisation of systems for reading and computer processing of optical images. It is known that the response time of photoelectronic devices is determined to a great extent by the photoemission inertia. The photoemission time of various photocathodes is investigated at the Department. Classical Ag – Cs – O and Na – K – Cs – Sb photocathodes, photocathodes with the negative electron affinity (NEA), and photocathodes fabricated by using modern nanotechnologies are being studied. The 'spread' of an electron packet in time, determined by the half-width $\Delta\varepsilon$ of the electron distribution over initial energies depends on many factors, in particular, the cathode material and thickness, the intensity and wavelength of the incident radiation, and the illumination type (direct or rear). It was found in experiments that for Ag – Cs – O photocathodes with the surface resistance of the order of $10\ \Omega\ \mathrm{cm}^{-2}$ developed at the Photoelectronics Department, the value of $\Delta\varepsilon$ is 0.1 eV at a wavelength of 1550 nm and broadens up to 2 eV at a wavelength of 395 nm.

A two-component Au + (Sb – Cs) photocathode has been fabricated which is sensitive both in the soft X-ray and visible spectral ranges. An ICT based on this photocathode has been fabricated and an X-ray camera providing the time resolution in the slit scan regime no worse than 10 ps has been custom-built for the Lebedev Physics Institute, RAS.

A new principle has been proposed for the fabrication of fast-response photocathodes based on a semiconductor $\mathrm{In_{0.53}Ga_{0.47}As/InP/Ag}$ heterostructure with the Schottky barrier [12]. In the case of a back bias produced by an external electric field in such photocathodes, the electric field propagates inside a working layer and photoelectrons drift to the surface with the maximal velocity achieving $\sim 10^7\ \mathrm{cm\ s^{-1}}$ for InGaAs. Therefore, the response time of the photocathode for a 1-μm-thick working layer cannot be shorter than 10 ps. At the same time, the sensitivity of NEA photocathodes at a wavelength of 1.55 μm exceeds that of the best Ag – O – Cs cathodes by two orders of magnitude.

Metal nanoparticles have been prepared in a superhigh vacuum (5×10^{-11} Torr) and their growth dynamics has been studied by the methods of X-ray and electron spectroscopy. It has been shown that photoemission in such structures is caused by excitation of surface plasmons. Because the transport of photoelectrons to a surface is absent in this case, photocathodes based on metal nanoparticles can have the short response time (~ 10 fs), which does not exceed the lifetime of plasmons. Photocathodes based on Ag and Au particles fabricated in our Department operate in transmission upon the normal incidence of light in the spectral range from 350 to 800 nm [13, 14]. Earlier, photocathodes based on the surface photoeffect could operate only in reflection at large angles of incidence of light, which prevented their use in femtosecond ICTs, in which the photocathode – grid distance should be principally small (a few hundreds micromeres). We have fabricated an ICT with a photocathode based on Au nanoparticles doped with Cs and O, which was inserted into the device with the help of a vacuum manipulator. It has been shown that photoeffect in such structures is determined by the probability of tunnelling of nonequilibrium photoelectrons through a potential barrier formed by the activating layer. In the approximation of a triangle potential barrier for photocathodes based on Ag and Au nanoparticles and also for Ag – O – Cs photocathode, the agreement between calculated and experimental photoemission spectra was obtained. Such a concept of the photoelectron emission allows us to find new ways for increasing the sensitivity of nanostructured photocathodes in the IR spectral region.

5. Theoretical support for pico – femtosecond photoelectronics studies

A further advance to the femtosecond range poses in a new way the problem of computer simulation and improvement of the mathematical software for designing modern photoelectronic devices. At the Department, the theoretical and algorithmic bases have been developed for computer simulations of time-analysing ICTs and diffractometers, and applied software packages (ELIM/DYNAMICS MASIM) have been created, which are based on the modern methods of computational mathematics and electron optics: the method of integral equations of the potential theory, the theory of difference schemes, asymptotic methods of the perturbation theory, the theory of aberrations of emission imaging systems, etc. [15].

One of the recent achievements of the Photoelectronics Department in the field of computational electron optics is the development of the theory of spatiotemporal focusing of photoelectron beams in nonstationary electric fields [16], which allowed us to build a unique photoelectron gun providing more than 50-fold time compression of photoelectron bunches [17]. This is achieved due to the creation of a new generation of focusing lenses in which, except a traditional stationary electromagnetic lens for formation of spatial photoelectron images, an additional nonstationary electron lens is used for temporal focusing. Computer simulations have shown, for example, that for a 15-fs laser pulse incident on the photocathode, the duration of an electron pulse on a target can be 350 as.

6. Photoelectron guns for electron diffraction experiments

The possibility of generating ultrashort electron-beam pulses initiated studies at the Photoelectronics Department aimed at the development of photoelectron guns for time-resolved electron diffraction (TRED) experiments. The operation principle of a photoelectron diffractometer is based on the spatiotemporal analysis of a diffraction pattern appearing upon scattering of a 30 – 50-keV pulsed femtosecond electron beam by the object under study (Fig. 2). During the development of photoelectron guns, there is no need to preserve in the photoelectron beam the initial spatiotemporal information on the optical signal incident on the photocathode. The main problem is to make a pulsed electron beam as short as possible to provide the maximum possible time resolution of the diffraction image.

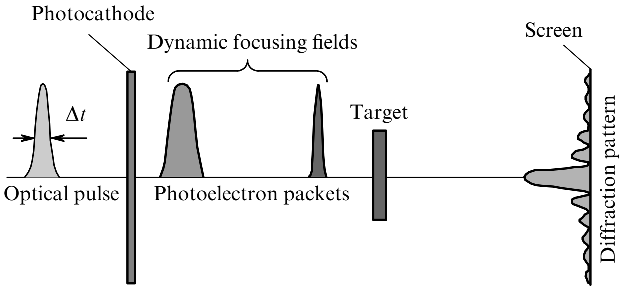


Figure 2. Formation of photoelectron bunches in a dynamically focusing system.

Theoretical foundations for the development of systems for generating ultrashort electron-beam pulses for diffractometry were experimentally realised in two directions. First, systems with electrostatic focusing fields were developed, and then, systems with dynamic focusing of photoelectron beams. The aim of these studies was to create a fundamentally new instrument – a femto – attosecond diffractometer for investigations of the fundamental properties of matter by recording the structural kinetics of matter at the atomic – molecular level. A diffractometer with a conventional stationary focusing lens developed and built at the Photoelectronics Department (Fig. 3) produces single photoelectron bunches of duration less than 500 fs containing up to $10^3 - 10^5$ 30-keV photoelectrons [18]. The angular divergence of the electron beam in the crossover was $10^{-2} - 10^{-3}$ rad and the beam spot size was 0.5 – 0.7 mm. The operation of the photoelectron diffractometer gun was demonstrated by studying diffraction pattern from a 300-Å aluminium foil. The diffraction pattern for this foil was preliminarily recorded with a conventional electron diffractometer by using an exposure time of 7 s and 50-μA beam current. The same pattern was obtained during a laser shot in the femtosecond diffractometer.

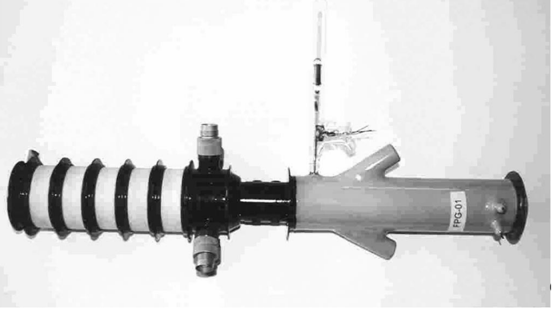


Figure 3. Experimental femtosecond diffractometer with a stationary focusing lens.

Figure 4 demonstrates a photoelectron diffractometer gun of a new generation, which is based on the dynamic compression of photoelectron beams [19]. Upon irradiation of the photocathode of this gun by 800-nm, 150-ps laser pulses, the duration of 'compressed' 10-keV electron pulses was 3 ps (Fig. 5) when the rate of change of the focusing voltage was 10^{12} V s^{-1}. When the slope of the focusing voltage was increased up to 4×10^{12} V s^{-1}, 10-ps photoelectron pulses (observed upon irradiation of the cathode by a laser diode at 860 nm) 'compressed' down to 285 fs.

Figure 4. Photoelectron gun with a dynamic focusing lens for time-resolved electron diffraction experiments.

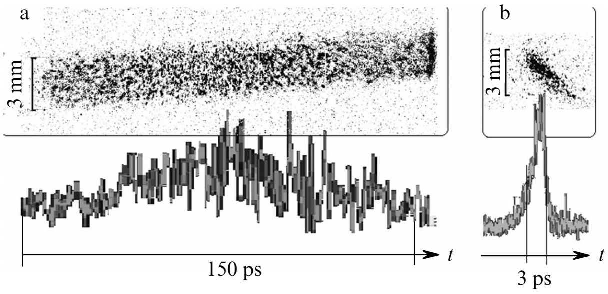


Figure 5. Initial (a) and compressed (b) 'image' scans of an electron packet on a screen and corresponding densitograms.

7. Development of the electron – optical instruments

It is obvious that new scientific advances are directly related to the level of development of scientific instrument making, in particular, devices for high-speed electron – optical diagnostics. One of the most prominent recent events is the continuous functioning of a research technological line created at the Photoelectronics Department in the late

1980s on initiative of A.M. Prokhorov for the design, development and manufacturing of the experimental samples of time-analysing ICTs, photoelectron guns, and cameras based on them. This unique research technological line provides the closed cycle of works, beginning from the formulation of the problem to the manufacturing of final products. Researchers at the Department perform studies in the fields of theoretical electron optics and computer simulations. Investigations on photoemission and improvement of photocathodes are carried out; specialised laser benches for the precision dynamic calibration of ICTs and streak cameras are manufactured and time-analysing ICTs, streak cameras, and photoelectron diffractometer guns are designed, manufactured, tested, and used in physical experiments.

The Department has two clean rooms, which are used, in particular, for assembling electrodes for focusing lenses and electron-image control systems. We have various mechanical equipment including lathes and milling machines, optical instruments and grinding lathes, as well as equipment for laser, electric-spark, argon-arc, high-frequency (Foucault currents) and flame welding. The glass-blowing workshop satisfies the entire complex of modern requirements. A station for hydrogen annealing equipped with two double-cap furnaces and a double-cap furnace for vacuum annealing is located separately. Conducting coatings are deposited on the inner surfaces of vacuum devices in high-vacuum thermal-sputtering facilities. Eight vacuum stations with the high-vacuum (down to 10^{-9} Torr) oilless pumping and heating up to 450 °C were used for processing the vacuum envelopes of ICTs and formation of photocathodes.

Two ultrahigh-vacuum (down to 10^{-11} Torr) stations are used in experiments for production of nanostructured photocathodes. Several leak detectors are employed, in particular, a supersensitive helium leak detector for detecting vacuum leaks at residual pressures of $10^{-11} - 10^{-12}$ Torr. Luminescent screens are applied on fibre discs and glass substrates by cataphoresis technique. The light efficiency and spatial resolution of manufactured screens are measured by using a special setup developed in the Department, which produces electron images in the form of a test pattern with the electron-beam energy controllable from 0 to 30 keV.

At present a few hundreds of time-analysing ICTs are developed and manufactured in the Department, including ICTs providing the time resolution in the slit scan regime better than 100 fs (Fig. 6) [20]. The spatial resolution of ICTs is 30 – 50 lines mm^{-1} and their sensitivity is sufficient for detecting a few tens of individual photons incident on the photocathode in the spectral range from soft X-rays (1 – 10 nm) to the near-IR region (1600 nm). Photoelectron guns performing manifold temporal compression of initial photoelectron beams have been calculated, simulated, and manufactured. In the near future we plan to fabricate photoelectron guns generating 20 – 50-keV electron bunches of attosecond duration.

Researchers at the Photoelectronics Department have developed and fabricated tens of high-speed streak cameras based on time-analysing ICTs [21]. These cameras operate in single-frame and multi-frame regimes of photographing rapid processes, synchronous scan, and slit scan (streak) regime. They cover broad temporal and spectral ranges. For example, one of the recent developments is a streak camera with a time resolution of 10 ps, which is sensitive both in the

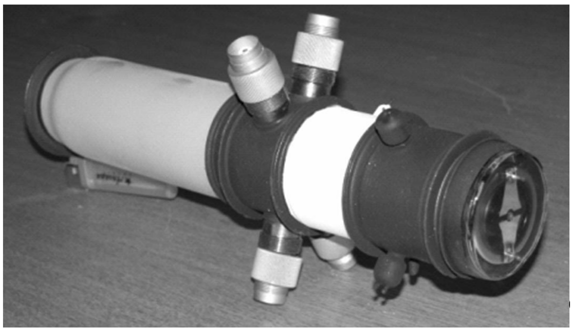
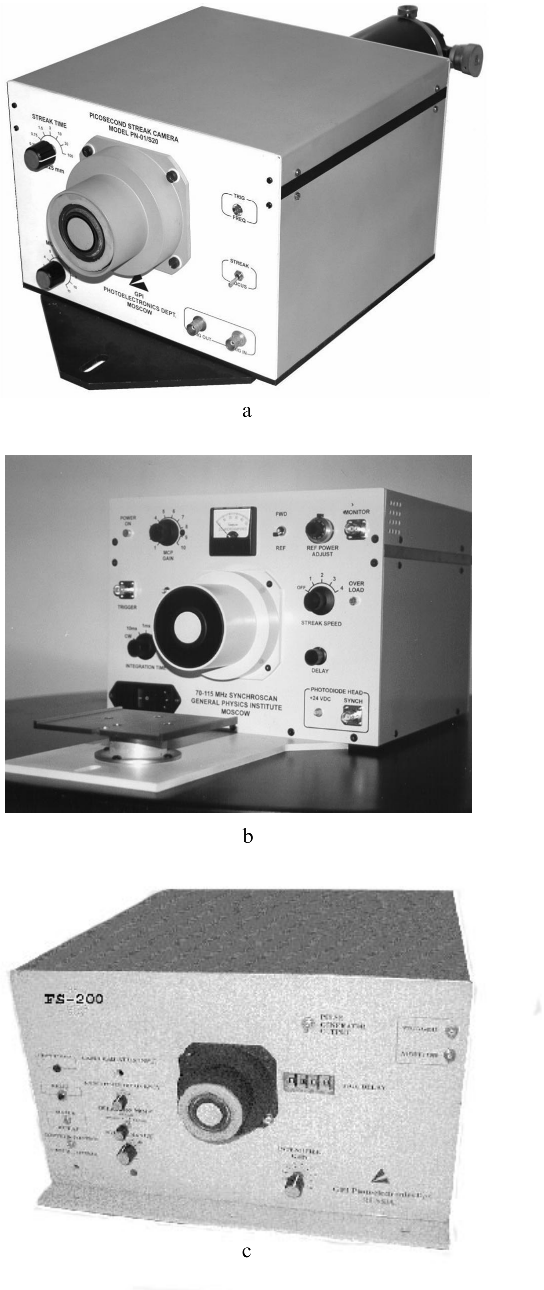


Figure 6. General view of a femtosecond PV-FS-M ICT.



a

b

c

Figure 7. Pico – nanosecond streak camera (a), synchroscan (b), and pico – femtosecond streak camera (c).

visible and soft X-ray ranges. Figure 7a shows a pico-nanosecond streak camera manufactured at the Department in small batches on individual orders, Fig. 7b shows a synchroscan streak camera operating at scan rates from 70 to 115 MHz, and Fig. 7c demonstrates a streak camera providing the time resolution no worse than 200 fs. Such cameras have been supplied to the Lebedev Physics Institute, the Institute of Semiconductor Physics, Siberian Branch, RAS, the Institute of High Temperatures, RAS, the Central Aerohydrodynamics Institue, and other organisations.

Due to the international scientific and technical collaboration in the field of high-speed electron-optical instrument making initiated by A.M. Prokhorov, many of the streak cameras have been created in collaboration with the leading companies around the world such as Hadland-Photonics (England), Cordin (USA), Hamamatsu (Japan), Thomson-CSF (France), V-Tek (South Korea), and Optronis (Germany). A good example is the Imacon-500 steak camera with a limiting time resolution of 1.5 ps (Fig. 8a); hundreds of these cameras are used at scientific laboratories in many countries. This camera has been developed in collaboration with Hadland-Photonics. A batch of picosecond streak cameras operating in the streak and synchroscan regimes (Fig. 8b) has been produced by the PROSCHEN (Prokhorov, Schelev, Nebeker) Russian – American Joint-Venture company. Extensive experimental studied have also been performed in collaboration with Hamamatsu Photonics Co. (Japan) (Fig. 8c). Streak cameras manufactured in our Department and in cooperation with other companies are successfully used by researchers in Russia and abroad in a variety of fields in science and technology, in particular, in laser and plasma physics, fibre and nonlinear optics, biological medicine and nanosurgery, femtochemistry and synthesis of new materials, and in defence technologies.

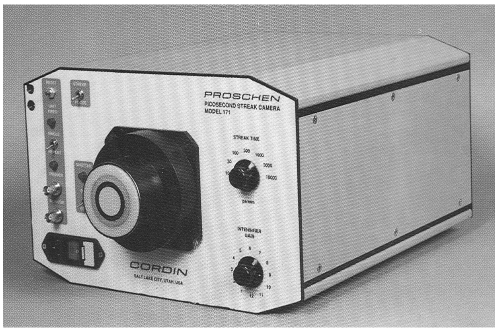
8. Conclusions

The scientific school created by A.M. Prokhorov in the field of laser-oriented high-speed electron-optical diagnostics of rapid processes has had a great international authority and combines highly qualified experts for many years. The results of our studies are reported in many publications (about 500), including educational manuals and books. Our achievements have been awarded by many Russian and International prizes. Beginning from 1968, the researchers of our Department have always participated in the International Congresses on High-Speed Photography and Photonics (ICHPP), presenting plenary and invited reports. We have organised two times these congresses in Moscow (14th Congress in 1980 and 23rd Congress in 1998). Academician A.M. Prokhorov was the president of the 23rd ICHPP, and the head of the Photoelectronics Department have been the Russian national delegate in the International Committee on High-Speed Photography and Photonics beginning from 1970 to the present.

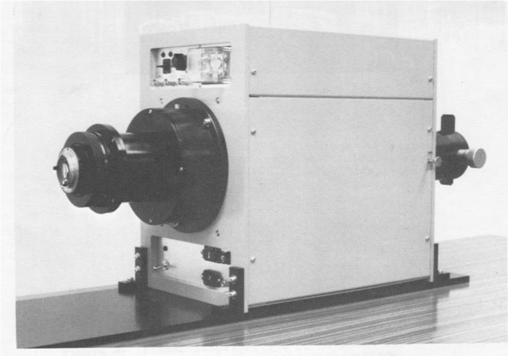
Superhigh-speed photoelectron technologies are being developed in the direction of improving the time resolution, which is now approaching its physical limit estimated as 10 fs for photoelectron imaging and 10 as (10^{-17} s) for formation of photoelectron packets ($E = 20 - 50$ keV). Researchers at the Photoelectronics Department, GPI actively participate in this creative process.

Acknowledgements. The author thanks M.A. Monastyrskii,

a



b



c

Figure 8. Imacon-500 (a) and PROSCHEN (b) cameras and the experimental electron – optical measuring system with the limiting time resolution of 1.4 ps (c).

E.L. Nolle, V.P. Degtyareva, E.A. Kuz'menko, V.I. Lozovoi, Yu.N. Serdyuchenko for their help in the writing of this paper, as well as all the researchers of the Photoelectronics Department, GPI, RAS.

References

1. Courtney-Pratt J.S. *Research, Suppl.*, **2**, 287 (1949); *Photogr. J.*, **92B**, 137 (1952).
2. Zavoisky E.K., Fanchenko S.D. *Dokl. Akad. Nauk SSSR*, **108**, 218 (1956); *Appl. Opt.*, **4**, 1155 (1965); *Dokl. Akad. Nauk SSSR*, **226**, 1062 (1976).
3. Butslov M.M., in *Uspekhi nauchnoi fotografii* (Advances of Scientific Photography) (Moscow: Nauka, 1959) Vol. 6, p. 76; Butslov M.M., Stepanov B.M., Fanchenko S.D. *Elektronno-opticheskie preobrazovateli i ikh primenennie v nauchnykh issledovanoyakh* (Electron – optical Converters and Their Application in Scientific Studies) (Moscow: Nauka, 1978).
4. Zavoisky E.K., Fanchenko S.D. *Dokl. Akad. Nauk SSSR*, **100**, 661 (1955).
5. Korobkin V.V., Schelev M.Ya., in *Proc. 8th Intern. Cong. High-Speed Photography* (Stockholm, Sweden, 1968), p. 36; *Zh. Tekh. Fiz.*, **41**, 216 (1971).
6. Korobkin V.V., Malyavin L.P., Schelev M.Ya. *Prib. Tekh. Eksper.*, **4**, 129 (1965); **3**, 145 (1966); **6**, 214 (1968).
7. Schelev M.Ya. *Usp. Fiz. Nauk*, **170**, 1002 (2000); *Kvantovaya Elektron.*, **31**, 477 (2001); **33**, 609 (2003) [*Quantum Electron.*, **31**, 477 (2001); **33**, 609 (2003)].
8. Bukin V.V. et al. *Kvantovaya Elektron.*, **36**, 638 (2006) [*Quantum Electron.*, **36**, 638 (2006)].
9. Dianov E.M., Fortov V.E., et al. *Pis'ma Zh. Eksp. Teor. Fiz.*, **83**, 84 (2006).
10. Vorob'ev N.S., Korobkin V.V. *Trudy FIAN*, **155**, 200 (1985).
11. Babushkin A.V., Vorob'ev N.S., Prokhorov A.M., Schelev M.Ya. *Kvantovaya Elektron.*, **16**, 2036 (1989) [*Sov. J. Quantum Electron.*, **19**, 1310 (1989)].
12. Nolle E.L., Prokhorov A.M., Schelev M.Ya. *Dokl. Ross. Akad. Nauk*, **348**, 45 (1996).
13. Nolle E.L., Schelev M.Ya. *Pis'ma Zh. Tekh. Fiz.*, **30**, 304 (2004); *Zh. Tekh. Fiz.*, **75**, 136 (2005).
14. Nolle E.L. *Usp. Fiz. Nauk*, **177** (10), 1133 (2007).
15. Greinfel'd D.E., Monastyrskii M.A., et al. *Proc. SPIE Int. Soc. Opt. Eng.*, **6278**, 15 (2006).
16. Monastyrskii M.A. et al. *Proc. SPIE Int. Soc. Opt. Eng.*, **4948**, 305 (2002).
17. Monastyrskii M.A. et al. *Nucl. Instr. & Methods in Phys. Research* A (in press).
18. Schelev M.Ya. et al. *Opt. Eng.*, **37**, 2249 (1998).
19. Andreev S.V. et al. *Proc. SPIE Int. Soc. Opt. Eng.*, **6279**, 701 (2006).
20. Dyagtereva V.P., Belolipetskii V.S., et al. *Proc. SPIE Int. Soc. Opt. Eng.*, **4948**, 281 (2002).
21. Schelev M.Ya., in *Entsiklopediya nizkotemperaturnoi plazmy* (Encyclopaedia of Low-temperature Plasma). Ed. by V.E. Fortov (Moscow: Yanus-K, 2006) Vol. V-1, p. 148.