CONFERENCES AND SYMPOSIA

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Modern problems in the physical sciences
(Scientific session of the Physical Sciences Division of the Russian Academy of Sciences, 16 November 2011)

DOI: 10.3367/UFNe.0182.201206e.0649

On 16 November 2011, the scientific session of the Physical Sciences Division of the Russian Academy of Sciences (RAS) was held at the conference hall at the Lebedev Physical Institute, RAS.

The agenda of the session announced on the RAS Physical Sciences Division website www.gpad.ac.ru included the following reports:

(1) **Schelev M Ya** (Prokhorov General Physics Institute, RAS, Moscow) "Pico-femto-attosecond photoelectronics";

(2) **Dal'karov O D** (Lebedev Physical Institute, RAS, Moscow) "The physics of low-energy antiprotons and antimatter";

(3) **Polukhina N G** (Lebedev Physical Institute, RAS, Moscow) "Nuclear track detection: advances and potential in astrophysics, particle physics, and applied research";

(4) **Vedeneev S I** (Lebedev Physical Institute, RAS, Moscow) "High-temperature superconductors in high and ultrahigh magnetic fields".

Papers written on the base of reports 1, 3, and 4 are presented below.

Uspekhi Fizicheskikh Nauk **182** (6) 649 – 676 (2012)
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Pico-femto-attosecond photoelectronics: looking through the lens of half a century

M Ya Schelev

1. Introduction

The late 1940s and early 1950s saw the development of a new area in technical physics — pico-femtosecond image-convertor chronography, whose physical foundations were created in our country by the work of Zavoisky's scientific school [1, 2]. This rather informative method for spatio–temporal analysis of fast processes is based on the employment of image-converter tubes (ICTs) converting optical images to photoelectron images and featuring a heightened frequency of the information channel, a high response of the external photoelectric effect, inertia-free control of electromagnetic fields, and the presence of means for digital data processing. Optical images at the photocathode are converted into the corresponding photoelectron analogs followed by the focusing, amplification, and deflection of photoelectron images which are spatially restricted by a point or a narrow streak over an ICT display [point image sweep or slit image sweep (so-called streak) cameras]. In 1949, Courtney-Pratt [3, 4] performed his first experiments on sweeping slit photoelectron images in a rapidly changing magnetic field and managed to record images of separate phases of an exploding substance with a streak speed of 3×10^7 cm s^{-1} and a maximal temporal resolution of 3×10^{-10} s. Somewhat later, Zavoisky, Fanchenko, and co-workers at the Kurchatov Institute of Atomic Energy constructed the first chronographic camera built around domestic UMI-95 type multistage ICTs developed by M M Butslov specially for high-speed photography [5, 6]. With this camera, they recorded separate emission phases of a high-frequency spark discharge with a point sweep speed of 10^9 cm s^{-1} and the maximal temporal resolution of 10^{-11} s. Note that, due to multistage image intensification ($10^5 - 10^6$), each individual photoelectron leaving the input photocathode was detected. In 1961, the same authors constructed a UMI-95V type ICT in which the electric field strength near the input photocathode was increased by an order of magnitude over that in the UMI-95 ICT (to 0.6 kV mm^{-1}), while the sweep speed of point photoelectron images was increased to 2×10^{10} cm s^{-1}, providing a technical temporal resolution achieving 5×10^{-13} s [7]. The results of these unique experiments stimulated theoretical studies of the fundamentals of high-speed image-convertor photography and establishing the limit of its temporal resolution, which was estimated at the level of 10^{-14} s [8–10].

Domestic advances in the field of pico-femtosecond image-tube chronography were appreciated by Prokhorov [11]. With his all-round support and active participation, Butslov, Stepanov, and their co-workers at the All-Russian Research Institute of Optical Physical Measurements (VNIIOFI in *Russ. abbr.*) began to develop a new generation of ICTs with an accelerating mesh near a photocathode and a microwave deflecting system [12, 13]. Peering through a half-century time lens into the history of the development of laser-oriented image-tube instrumentation making at the Lebedev Physical Institute (FIAN) and the Prokhorov General Physics Institute (IOF RAN), we note that, beginning from the 1960s, the ICTs were a reliable tool used in laser physics for studying

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fast processes, which could not be investigated by other known methods and instrumentation, whereas lasers provided reliable landmarks for the development of ICTs [14–17]. Simultaneously with the development of new lasers emitting shorter pulses, the aim of these studies was a continuous improvement in the temporal resolution of ICTs, which was 10^{-11} s in 1968, 7×10^{-13} s by 1976, 2×10^{-13} s by 2001, and now is better than 10^{-13} s. The most noticeable advances in this field were achieved by recording the radiation from a Ti:sapphire laser with a temporal resolution of $(1.6-2) \times 10^{-13}$ s in the streak mode with a sweep speed of 5×10^{10} cm s^{-1} [18]. Thus, from the moment of the construction of the first streak camera till now, the temporal resolution of ICTs has improved by more than three orders of magnitude. However, the totality of technical problems encountered during the last two decades have considerably slowed down this trend and prevented the achievement of the predicted theoretical limit of 10^{-14} s.

A new milestone in the experimental realization of the femtosecond temporal resolution in photoelectronics was reached with our proposal to compress photoelectron beams in nonstationary focusing fields [19]. An initial 7×10^{-12} s photoelectron bunch was compressed to 2.8×10^{-13} s. Theoretical estimates show that it is possible, in principle, to produce attosecond (10^{-18} s) long electron bunches in nonstationary focusing fields [20]. Such bunches, apart from their direct use in time-resolved electron diffraction (TRED) experiments [21–26], can also be successfully employed for testing systems designed for sweeping photoelectron images in ICTs, which determine eventually the limiting accuracy of femtosecond-resolved spatio-temporal measurements.

Below, we discuss our main advances during the last decade in the development of ICTs with temporal resolution in the range from 10^{-12} to 10^{-13} s. Based on our previous studies [27, 28], an attempt is made to determine the most rational paths for focusing efforts in this area.

2. On the way to overcoming the 100-femtosecond barrier in image-tube streak photography

Summarizing the results of the development of image-tube photography on the threshold of the third millennium, the 23rd International Congress on High-Speed Photography and Photonics held at FIAN (Moscow) in 1998 concluded that image-convertor chronography had completely mastered the picosecond range [29]. At the same time, this brought up the important question: What is the limiting temporal resolution that streak cameras can provide in today's physical experiments, in particular, with the employment of modern lasers generating optical pulses with a duration of only a few femtoseconds?

Analysis shows that razing this last bastion in image-tube photography, i.e., the achievement of the temporal resolution in experiments in the range of 10^{-13} to 10^{-14} s, requires the resolution of many practical issues, some of which are listed below.

(1) The development of fast nanostructured photocathodes sensitive in the spectral range from soft X-rays to the near IR region, with a surface resistance of a few ohms per square ($\Omega/\square$).

(2) An increase in the electric field strength nearby a photocathode to 30–100 kV mm^{-1}.

(3) A decrease in the spread of initial photoelectron energies to 0.05–0.1 eV taking into account energy-level shifts in 100–300-Å-thick photocathode films in the intense accelerating field mode applied to the photocathode–mesh gap in femtosecond ICTs.

(4) An increase in the phase sweep speed of photoelectronic images on an output detector (a luminescent screen or electron-sensitive charge-coupled device (CCD) array to 3–10 speeds of light.

(5) At least an order of magnitude improvement in the signal-to-noise ratio for photoelectronic images swept on the ICT display.

(6) The development of aberration-free optics for imaging fast processes on an ICT photocathode (a spatial resolution of at least 30–50 pairs of lines per mm, with an image formation time of a few femtoseconds).

(7) The minimization of the roughness of the substrate surface under a photocathode surface to a few nanometers

(8) The construction of a photocathode–mesh unit allowing the application of 10–50-kV subnanosecond long pulses.

(9) The optimization of a focusing lens taking higher-order aberrations into account, in particular, by applying magnetic focusing and transaxial optics.

(10) The replacement of capacitor type deflecting and gating systems by traveling microwave systems.

(11) The employment of the most advanced image intensifiers providing a conversion factor of at least 10^4–10^6 for a signal-to-noise ratio $\geqslant 10-100$.

(12) The choice of supersensitive and low-noise CCD reading systems for digital processing of time-resolved images, including the use of electron-sensitive CCD arrays minimizing the loss of information in objectives and fiber optic splicings.

It follows from this list of issues that a head-on attack for achieving the limiting temporal resolution (10^{-14} s) requires huge efforts. For example, taking account of only first-order chromatic aberrations in a focusing lens of an ICT (i.e., only a spread in the initial velocities of photoelectrons, as in the pioneering work of Zavoisky and his colleagues), is no longer sufficient for the correct estimate [30] of the temporal resolution of an ICT in the range shorter than 200 fs (Fig. 1). As follows from Fig. 1, if only first-order aberrations are taken into account, a 5-fold increase in the electric field strength near the photocathode (from 5 to 25 kV mm^{-1}) should also improve the temporal resolution by five times (from 350 to 70 fs). However, taking second-order aberra-

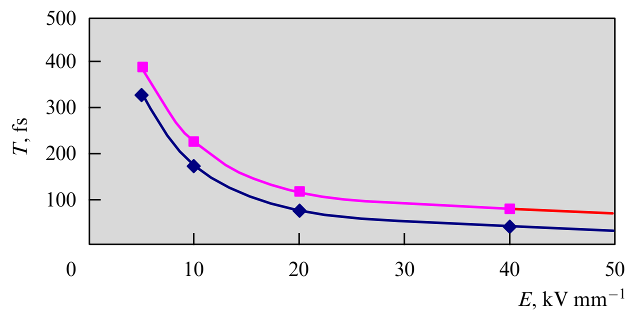

Figure 1. Calculated temporal resolution of an ICT with a three-electrode focusing lens as a function of the electric field strength nearby the photocathode: the lower curve is calculated taking into account only first-order chromatic aberrations, and the upper curve is calculated with first- and second-order aberrations.

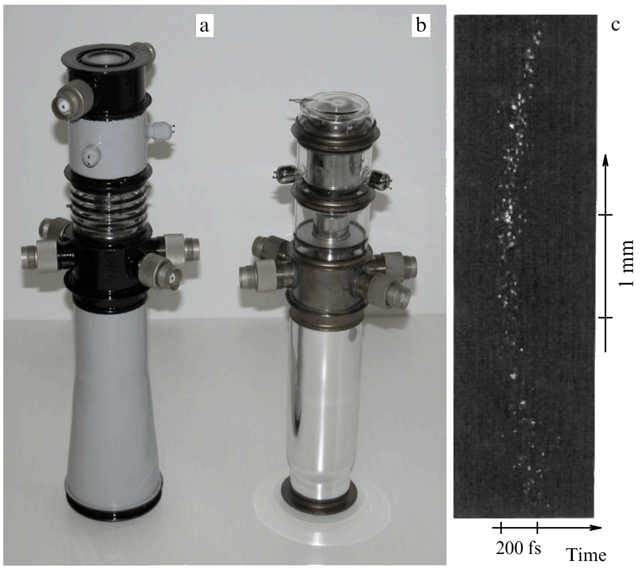

Figure 2. Femtosecond ICTs: PV-FS with coaxial-strip-line (a) and PV-FS-M with capacitive (b) configurations of the photocathode–mesh unit. The streak picture of a swept laser pulse with an initial duration of 120 fs (determined with an autocorrelator) on the PV-FS phosphor screen (c).

tions into account, the temporal resolution improves by only 3.5 times (from 400 to 120 fs). In other words, the increase in the field strength nearby the photocathode from 25 to 50 kV mm^{-1} barely noticeably improves the temporal resolution. The reason is the influence of higher-order aberrations which can be compensated by increasing the energy of an electron beam carrying information about the input image.

Our efforts for more than a decade in the development and tests of femtosecond ICTs of a new generation with a pulsed power supply of the photocathode–mesh gap have confirmed this conclusion. In 2001, a PV-FS type ICT with a measured temporal resolution approaching 160 fs was designed, manufactured, and tested by researchers at the Department of Photoelectronics at IOF RAN (Fig. 2a) [31]. Figure 2c shows a chronogram of a 120-fs, 800-nm, $(1-5)\times10^3$-W-cm^{-2} pulse from a Ti:sapphire laser swept on a PV-FS phosphor screen with the phase streak speed of 5×10^{10} cm s^{-1} and electric field strength nearby the photocathode of 13 kV mm^{-1}. In this case, the photocathode sensitivity at a wavelength of 800 nm was 0.5 mA W^{-1}, the photocathode–mesh gap measured 0.47 mm across, and the accelerating voltage across the photocathode–mesh gap was about 6 kV.

The next modification due of this ICT utilized a modified configuration of the photocathode–mesh unit in the form of a lumped capacitance. In a PV-FS-M tube [32], a low-resistance $(1-5\ \Omega/\square)$, silver–oxygen–caesium photocathode was grown, which was sensitive in the spectral range from 115 to 1550 nm, and photoelectronic image sweep and gate systems were optimized (Fig. 2b). Computer estimates accounting for higher-order aberrations for this ICT configuration gave the maximum temporal resolution of 97 fs at the photocathode center and 320 fs at a distance of 3 mm from the center, for an electric field strength near the photocathode exceeding 40 kV mm^{-1} (15-kV, 2-ns pulses need to be applied across the 0.35-mm photocathode–mesh gap). Further numerical experiments with the PV-FS-M ICT showed that the maximal temporal resolution could be additionally improved 1.5- to 2-fold by applying an accelerating overall potential of no less than 25–30 kV across the photocathode–mesh gap. This result clearly confirms once more the importance of accounting for higher-order temporal aberrations.

Based on PV-FS and PV-FS-M tubes, experimental prototypes of femtosecond streak cameras were constructed [33]. They were equipped with specially developed relay optics with the femtosecond formation time of fast-process images in the photocathode plane by accounting for the group velocity dispersion in relay optics lenses. Subnanosecond pulsed control circuits developed for these cameras provided a triggering delay of 10 ns, with an instability of ±5 ps and a maximal phase speed of linear ($\pm5\%$ nonlinearity in time) streak sweep of photoelectronic images of up to 10^{11} cm s^{-1}.

Dynamic tests of these streak camera prototypes were performed using 10-fs, 35-fs, and 120-fs pulses from Ti:sapphire lasers providing the maximal input power density at the photocathode up to $(1-5)\times10^3$ W cm^{-2} (to record the entrance slit images in the static regime, a power density of $\sim 10^{-7}-10^{-8}$ W cm^{-2} was sufficient). For the entrance slit image 30 μm × 5 mm in size at the photocathode and the photocathode sensitivity of about 0.4 mA W^{-1} at a wavelength of 800 nm, time-resolved images were produced with assistance of 400–2000 photoelectrons. As a result, images recorded on the ICT phosphor screen consisted of separate luminous dots, on condition that a system for the subsequent display of time-resolved images provided reliable detection of each photoelectron escaped from the input photocathode. Remembering that it is the Coulomb repulsion that restricts the number of electrons that can be located within a spatially resolved element (no more than 1–10 electrons for achieving a temporal resolution of 10^{-14} s), we should admit that, to improve the accuracy of measurements with the employment of femtosecond streak cameras, it is necessary to perform the superposition (summation) of chronograms along the slit direction.

3. Photoelectron guns with nonstationary focusing fields as a breakthrough in femtosecond photoelectronics

Addressing ourselves to the physical principles at the base of ICT operation, recall that spatio–temporal optical images of fast processes are converted with a high accuracy at the ICT photocathode to the corresponding photoelectron analogs. This is confirmed by the linearity of the photoresponse to light intensity within six orders of its magnitude, while it is assumed that the photoemission event itself lasts no more than a few femtoseconds. Moreover, the planes of optical and photoelectron images coincide in space with an accuracy to a few hundred angstroms (the thickness of a photocathode film ranges 100–300 Å).

In the first ICT, constructed in the early 1930s in Germany and given the name 'Holst glass' [34], photoelectrons propagated from a photocathode to a screen in a uniform (accelerating) electric field. The spatial resolution ΔR in such an ICT (only several pairs of lines per mm) was fundamentally restricted by first-order aberrations:

$$\Delta R = 2d\sqrt{\frac{\varepsilon_r}{u}},$$

where ε_r is the radial component of the initial photoelectron energy, u is the accelerating potential, and d is the distance between the photocathode and the phosphor screen. An important result of the investigations of Scherzer [35], Artsimovich [36], and some other researchers on focusing photoelectron images in ICTs was the use of inhomogeneous static electromagnetic fields in which first-order spatial aberrations could be eliminated in the image plane (Gauss plane). After that, the diameter of an electron scattering circle is determined by higher-order aberrations. The effect of utilizing inhomogeneous focusing fields surpassed all expectations. The spatial resolution of the ICTs was considerably improved up to a few dozen pairs of lines per mm.

The question arose as to whether it is possible, similarly to the spatial focusing of photoelectronic images in inhomogeneous electrostatic fields, to perform the temporal focusing (i.e. a decrease in duration) of photoelectron beams in nonstationary electric fields. In some sense, the analogs here are some microwave devices utilizing the electron grouping effect and also time-of-flight mass spectrometers. Based on theoretical and computer analysis, Monastyrski et al. [19] showed that the first-order temporal chromatic aberration can be completely eliminated in a specially selected nonstationary focusing field (for example, in the filed of a hyperbolic electron mirror). This aberration, which cannot be eliminated in static focusing fields, is described by the famous Zavoisky–Fanchenko formula

$$\Delta T_{\mathrm{chr}} = \sqrt{\frac{2m}{e}}\,\frac{\sqrt{\varepsilon}}{E}\,,$$

where m and e are the electron mass and charge, respectively, E is the electric field strength nearby the photocathode surface, and ε is the half-width of the energy distribution of photoelectrons leaving the photocathode. Temporal compression of the photoelectron beams is provided by the additional energy spread introduced by the time-dependent electric field into the electron beam, so that particles at the trailing edge of the beam begin to move faster than particles at the leading edge of the beam. After some time, the 'rear' particles overtake the 'front' particles, and the electron beam duration becomes minimal at this moment, which determines the position of the temporal focus. An important advantage of using nonstationary focusing fields is that spatial charge effects can be considerably compensated (by an order of magnitude) by the optimal choice of the amplitude and slope of nonstationary focusing fields.

The prototype of a femtosecond photoelectron gun calculated, designed, and manufactured at the Department of Photoelectronics at IOF RAN by using applied ELIM/DYNAMICS [37, 38] and MASIM 3D [39] software packages is shown in Fig. 3a [40]. The unique feature of this gun is that for the first time in the history of image-tube instrumentation making it provides the temporal and spatial focusing of photoelectron beams simultaneously! Our numerous experiments performed with this photoelectron gun confirmed the possibility of multiple (25–50 times) compression of the photoelectron beams. As an example, Fig. 4a demonstrates the chronogram of an initial 7-ps laser pulse whose duration was reduced to 285 fs (Fig. 4b) in the focusing field of the gun (the focusing pulse amplitude and steepness of a pulse edge were 960 V and 2.4×10^{12} V s^{-1}, respectively, and the sweep speed amounted to 8.4×10^{10} cm s^{-1}).

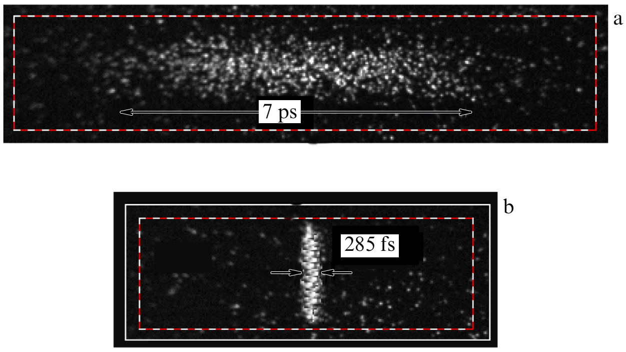

Figure 4. Streak pictures of a 7-ps laser pulse swept on the photoelectron gun phosphor screen (a), and of the same pulse after its compression to 285 fs in nonstationary focusing fields (b).

The next step in mastering the femtosecond time range was our proposal to develop a multifunctional photoelectron device combining the functions of a femtosecond ICT and a femtosecond photoelectron gun for studying the atomic and molecular dynamics of matter by 'transmission' TRED methods. Such a hybrid device was modelled, designed, manufactured, and tested in the static mode. The structure of the electrodes for this hybrid device is given in Fig. 3c, and its general view is presented in Fig. 3b. The calculated temporal resolution of the device in the time-analyzing ICT mode equals 110 fs. When an 8-kV pulse, linearly increasing for 0.5 ns, was fed to the temporal focusing electrode, the initial 110-fs pulse electron beam was compressed to a 35-fs pulse. Therefore, already today, with such a device in the photoelectron gun mode, we can produce an electron beam with a duration of a few dozen femtoseconds and then sweep it on the ICT phosphor screen, and thereby answer the question about the limiting accuracy of measuring such short signals by the methods of image-tube chronography.

The above facts allow us to assert that the Prokhorov General Physics Institute, RAS has priority in the development of the aberration theory of spatio–temporal focusing of photoelectron beams in nonstationary electric fields. We directly generalized the Zavoisky–Fanchenko formula to the

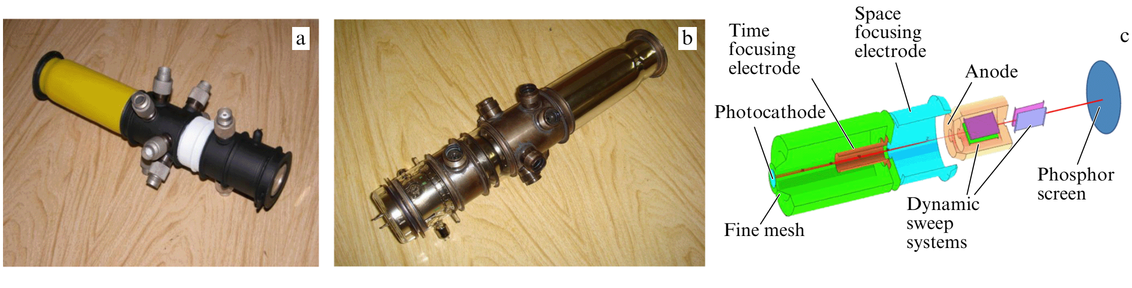

Figure 3. Femtosecond photoelectron gun (a), multifunctional ICT–photoelectron gun device (b), and its geometric configuration (c).

case of nonstationary focusing fields and showed that the application of such fields allows one to improve by at least an order of magnitude (i.e. reduce to a few fractions of a femtosecond) the theoretical limit of the temporal resolution caused by chromatic aberrations of ICTs with static focusing fields. The measurements performed with the help of femtosecond photoelectron guns manufactured at the Department of Photoelectronics at IOF RAN completely confirmed the results of theoretical calculations. In 2007, work covering the evolvement of theory and practical implementation of a femtosecond photoelectron gun at the Department of Photoelectronics received the highest rating at the competition of scientific research activities devoted to the 25th anniversary of IOF RAN's foundation.

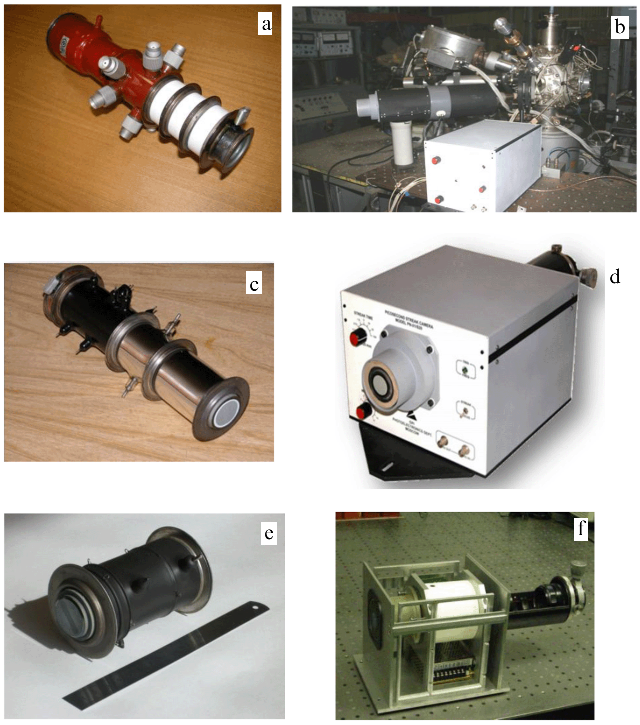

Figure 5. Innovation developments of the Department of Photoelectronics at IOF RAN: (a) a PV-003R ICT [12, 13] with a two-component (Au + CsSb) photocathode sensitive in the visible (360–650 nm) and soft X-ray (0.1–1 nm) spectral ranges; (b) a 10-ps camera based on above ICT, operating in the streak and single-frame modes (shown in a setup for laser fusion experiments at FIAN); (c) a PIF-01 ICT with a transfer type photocathode; (d) a PS1/S1 picosecond streak camera based on the PIF-01; (e) a meshless PF-M ICT with a large photocathode area, and (f) a portable 'multichannel oscilloscope' type streak camera based on the PF-M.

4. Innovative pico-femtosecond photoelectronics

IOF RAN's innovative activity and especially the international cooperation for many years with almost all the leading foreign scientific centers and companies specializing in the field of ultrahigh-speed image-tube instrumentation making [41] have allowed us to avoid a breakdown in own research and technological bases which, given current realities, were already receiving insufficient budget funding. The outstanding role in the conquest of the market of picosecond image-convertor devices belonged to the legendary domestic PV001 ICT [42]. This ICT was developed by G I Bryukhnevich, V A Miller, and co-workers at VNIIOFI in the mid-1970s and is protected by inventor's certificate [43] and patents in the USA, Great Britain, France, the Netherlands, and Japan. The PV001 ICT exemplified all the best achievements realized by Butslov and his scientific school in unsurpassed domestic PIM–UMI series devices, including devices equipped with an accelerating mesh. As early as 1976, we used the UMI-93M device to obtain a temporal resolution of 0.7 ps [44]. A few thousand samples of the PV-001 type ICTs were manufactured and became the base of small-batch EOK-2M and EOK-3 cameras [45] produced by the Special Design Bureau of Physical Instrument Making for the Vavilov State Optical Institute (GOI) and also of the famous mass-produced VNIIOFI Agat cameras [12, 13]. During our scientific and technical collaboration with the companies Hamamatsu (Japan), Hadland-Photonics, Specialized Imaging (UK), Cordin (USA), Thomson-CSF (France), Optronis (Germany), V-Tek (South Korea), etc., we developed and manufactured shown to advantage picosecond streak cameras based on PV series tubes, for example, a few hundred British Imacon-500 cameras [46]. In 2008, researchers at the Department of Photoelectronics manufactured for FIAN a 10-ps streak camera built around the PV-003R tube (Fig. 5a) with a two-component photocathode sensitive both in the visible and soft X-ray ranges (Fig. 5b).

Another example of our innovative activity is the PIF-01 type ICT developed at IOF RAN by V P Degtyareva and co-workers in 1984 and still manufactured in the amount of tens of devices on our own research and technological base (Fig. 5c) [47, 48]. By using PIF-01, V I Lozovoi and co-workers constructed a PS-1/S1 series picosecond image-tube streak camera (Fig. 5d), which advantageously differs from its foreign analogs by the high temporal resolution in the streak sweep mode (1 ± 0.2) ps for a sweep speed of $(1-2) \times 10^{10}$ cm s^{-1} and electric field strength of 3–4 kV mm^{-1} near the photocathode, a broad spectral range (350–1300 nm), a short triggering delay (< 15 ns), and low triggering instabilities (± 10 ps). IOF RAN delivered more than ten such cameras to domestic customers [FIAN; Institute of Semiconductor Physics, Siberian Branch of the RAS; Institute of Applied Physics, RAS; Institute for High Temperatures, RAS; Kotel'nikov Institute of Radioengineering and Electronics (IRE), RAS, etc.]. Vorob'ev, Gornostaev, Smirnov, Pelipenko, Shashkov et al. [49], researchers at the Department of Photoelectronics at IOF RAN, together with researchers at IRE RAS, performed experiments on the conditioning of the technical parameters of this camera to determine the possibility of its application for precision picosecond measurements in the field of semiconductor physics. These tests allowed the researchers to essentially improve the operation parameters of subsequent cameras and confirmed the efficiency of domestic developments, in particular, their low cost (2–3 times lower than the cost of analogous foreign devices). By the way, the PIF-001 tube was successfully utilized in a commercial model 173 streak camera still produced by Cordin (USA) [50].

The popular devices manufactured in the Department of Photoelectronics also include picosecond meshless PV-001-V, PF-01, and PF-M ICTs with a large photocathode area (diameter no less than 20–25 mm). For example, a meshless PV-001-V type ICT with a multialkaline photocathode (200–850 nm) with an operation-area diameter of 25 mm is used in the multichannel version of an Imacon-500 streak camera in the National Ignition Facility at Livermore. We specially developed a PF-01 ICT for use in a streak channel in a multiframe Imacon-468 camera (Hadland Photonics, Great Britain). In 1999, this camera received the highest Royal Award for Technological Perfection [51]. Such image-tube cameras, being coupled with spectral instruments or many fiber-optic detectors, should have a long slit to increase the amount of spatial information projected along the slit, which is simultaneously analyzed in time.

Using newly developed meshless PF-M tubes (Fig. 5e) with a photocathode input area of 4×20 mm, providing a spatial resolution of no less than 30 pairs of lines per mm and a temporal resolution of at least 50 ps, Yu N Serdyuchenko in the Department of Photoelectronics built a prototype of a universal streak camera (Fig. 5f) operating in a broad sweep speed time range (from 10 ns to 50 μs per screen). A camera built around a PF-M tube and an EP-10 microchannel image intensifier has a small size ($20 \times 20 \times 35$ cm) and small weight (less than 5 kg). There is good reason to believe that, due to its low cost, this innovative development could be used in the end for the mass production of these cameras. Having a cost comparable to that of a good oscilloscope, one such camera would be able to replace a few hundred oscilloscopes due to the simultaneous analysis of many measuring channels determined by the number of spatially resolved elements fitted along the camera slit height.

5. Conclusions

Let us define now the priorities for further developments in mastering the femto-attosecond time range in photoelectronics. Any photoelectronic device begins with a photocathode, and therefore a thorough study of the nature of the external photoelectric effect and the development of high-speed and highly sensitive photocathodes operating in a broad spectral range in intense accelerating fields near their surface are the most important issues. It is assumed that the intrinsic photoelectric effect in classical Ag–O–Cs (Si) cathodes that we widely use is determined by the tunneling probability of nonequilibrium photoelectrons through a potential barrier formed by an activating layer [52–55]. During growing, such a photocathode is formed in the reaction $Ag_2O + 2Cs \rightarrow 2Ag + Cs_2O$. Silver nanoparticles 10–50 nm in size in the photocathode are surrounded by the dipoles of ions Cs^+ and $Cs^+ - {}^-O^- - Cs^+$ (the dipole layer thickness is a few nanometers), which reduce the work function to 0.1–1 eV in the course of illumination by visible and IR radiation. Photoemission is caused by excitation of surface plasmons in nanoparticles, while the IR sensitivity is determined by the nanoparticle size, shape, and distribution over the surface. The transport of photoelectrons from the photocathode volume to its surface is absent. The photoemission lifetime coincides with the time of plasma wave propagation through a nanoparticle. If the size of nanoparticles is ~ 10 nm and the plasma wave velocity is $\sim 2 \times 10^8$ cm s^{-1}, the photoemission lifetime does not exceed 5 fs. This means that, to detect reliably photoelectron packets of such durations, it is necessary to further improve the ICT focusing and deflecting systems. This can be realized only based on thorough theoretical and computer investigations of modern time-analyzing ICTs taking into account the possibility of manufacturing their prototypes followed by the small-batch production of ICTs using the existing research and technological bases at IOF RAN. The preservation and development of the unique theoretical potential accumulated in the Department of Photoelectronics is the absolutely necessary condition for solving today's problems of femtosecond photoelectronics.

Along with the advisability of accelerating studies on the improvement of available PV-FS series femtosecond ICTs, our recent proposal to utilize transaxial lenses for focusing 'slit' images deserves special attention and rapid practical implementation. The paradox of the situation from the moment of realization of the streak sweep in 1949 is that almost all time-analyzing ICTs use focusing lenses with axial symmetry. This is explained by the fact that the initial night-vision devices and their subsequent analogs, specially developed for high-speed photography (for example, PIM-3), were intended for two-dimensional imaging, i.e. they could be applied both to frame-to-frame recording and to streak sweep.

To do justice, note that back in 1988, in collaboration with H Niu, a Chinese trainee at IOF RAN at that time, who is now an academician, we developed a 50-fs ICT with a plane-parallel focusing capacitor type lens [56, 57]. Using these developments, we manufactured and tested a BSHCHV ICT [58]. This ICT, which operated only with input slit images, at once showed promising results. In particular, the temporal resolution achieved with this ICT was 5×10^{-13} s for a sweep speed of 1.7×10^{10} cm s^{-1} and electric field strength nearby the photocathode equal to 6 kV mm^{-1}.

In 2010, D E Greenfield of the Department of Photoelectronics performed computer simulations of the newest configuration of a femtosecond ICT based on the application of transaxial focusing lenses (Figs 6a, b). Such an ICT can produce tightly focused electron beams with a virtually

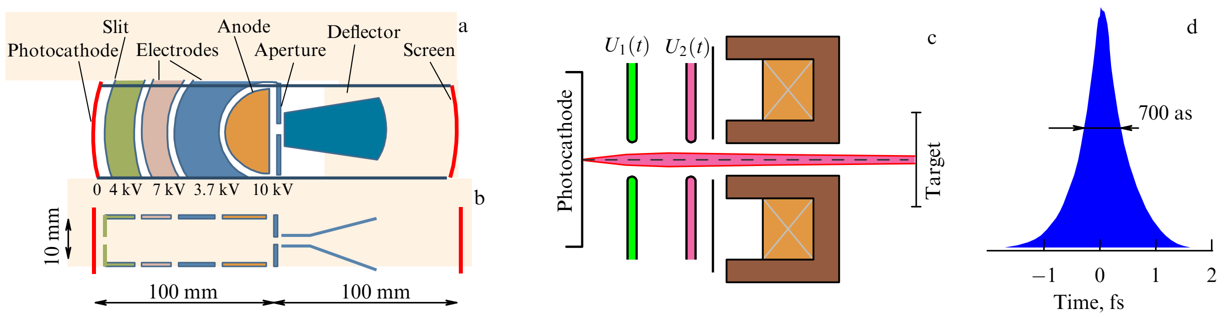

Figure 6. Construction of a femtosecond ICT with transaxial lenses: (a) top view along the slit, (b) side view (across the slit). (c) Schematic of a photoelectron gun with second-order aberration correction; U_1 and U_2 are rapidly changing pulsed electric fields. (d) Compression of a 50-fs photoelectron beam to 700 as (computer simulations).

unlimited length of the photocathode area along the slit. Thus, for an electric field strength of 4 kV mm^{-1} near the photocathode, the calculated temporal resolution of such ICT is none the worst than 0.45 ps for spatial focusing of 1–20 μm in two mutually perpendicular directions.

Our original studies on the compression of photoelectron beams in nonstationary focusing fields should be further activated, the more so to achieve the theoretical limit: two–three orders of magnitude still remain here, rather than an order of magnitude, as in the case of image-tube chronography. A very promising area covers the development of a femtosecond photoelectron gun with a correction of the second- and higher-order aberrations using successive systems for compressing electron beams in rapidly changing pulsed electric fields with additional focusing magnetic lenses (Fig. 6c). Our numerical simulations [59] done, in particular, together with German colleagues of the Max Planck Institute and supported by the Russian Foundation for Basic Research, confirm the possibility of producing electron beams with a duration of a few hundred attoseconds (Fig. 6d). Eventually, such beams can be focused to a fine spot a few hundred nanometers in diameter on a target.

As for the innovative activity, at present, apart from the PV-001, PV-FS, PIF-01, PF-01, PF-M series ICTs, a PS-1/S1 picosecond streak camera and a miniature oscilloscope type camera built around a PF-M tube are ready for small-batch production. The latter camera can successfully compete against the fastest oscilloscopes if we find a proper sponsor.

To realize all the plans mentioned above, a reliable and continuously operating research and technological chain is required, and in fact it was created at IOF RAN on the initiative of A M Prokhorov back in 1989 and still exists due to support from the management of IOF RAN headed by I A Shcherbakov. The tasks of this chain are as follows: the development and maintenance of pico- and femtosecond laser setups intended for the dynamic calibration of ICTs, streak cameras, and photoelectron guns; the development of software packages and computer simulations of image-tube focusing and deflecting systems; the design, technological development, and manufacturing of ICT prototypes and photoelectron guns and cameras based on them, and static and dynamic tests of photoelectron devices created at the Department of Photoelectronics and the ensuing development of methods of their application in physical experiments. The preservation, maintenance, and advancement of the research and technological potential in the field of ultrahigh-speed photoelectronics existing at IOF RAN are worthy objectives!

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Nuclear track detection: advances and potential in astrophysics, particle physics, and applied research

N G Polukhina

Results of nuclear physics research made using track detectors are briefly reviewed. Advantages and prospects of applying the track detection technique in particle physics, neutrino physics, astrophysics, and other fields are discussed for the example of the results of works at the PAVICOM facility of the Lebedev Physical Institute (LPI), Russian Academy of Sciences (PAVICOM: the Russian acronym for Completely Automated Measuring Complex). A unique facility PAVICOM satisfies the best world standards for track detectors and has been successfully operated for about 10 years now. The review covers the results of studies on the search for direct origination of the tau neutrino in a muon neutrino beam within the framework of the international experiment OPERA (Oscillation Project with Emulsion-tRacking Apparatus). LPI's PAVICOM made the possibility of scanning nuclear emulsions from OPERA's detector a reality, enabling the participation of Russian physicists in processing and analyzing the data of this experiment. The spectra of superheavy elements in galactic cosmic rays are presented; the spectra were obtained in measurements of the nucleus tracks in crystals of olivines from meteorites, and nuclei with charges within the range $105 < Z < 130$ *were registered. The prospects for using the track detection technique in, for example, neutrino physics studies (the search for double beta decay) and applied research into muon radiography (nondestructive testing of large construction sites, the search for mineral resources, etc.) are reported.*

Track detectors have been widely used in particle physics for very many decades. In track detectors, registration of elementary particles is accompanied by the emergence of observable traces (tracks) repeating the mechanical trajectory of an elementary particle. These are bubble and spark chambers, nuclear emulsions, silver chloride crystals, and etchable solid state track detectors [1–14]. The popularity and long lifetime of the track detection technique are not by chance and are due to a range of merits of the detectors: uniquely high spatial resolution, obviousness of the reconstructed spatial pattern of particle interaction, relative simplicity and low cost, capability of accumulating information over long periods of time, and some other advantages.

The technique started to develop with the work by Becquerel [1–3] in 1896. The first track detectors were common photographic plates — Becquerel discovered natural radioactivity when finding fogged (exposed) photoplates that were wrapped in an opaque material together with fluorescent potassium uranyl sulfate.

The so-called Wilson chamber makes use of the condensation of liquid from supersaturated vapor (under suitable conditions ionization produced in a substance by a traveling charged particle can cause a phase transition in it). The instrument was invented in 1912 by Wilson [4], who for many years had studied the physics of cloud formation in the terrestrial atmosphere. The bubble chamber was invented and improved in the early 1950s by Glaser [6] [a superheated liquid is used, which boils near the nucleation centers — local energy-release sites ($\geqslant 0.1$ keV) in the trajectory of a particle in the superheated liquid]. Wilson chambers and bubble chambers also make it possible to directly observe tracks of particles. This means that the position of a particle can be determined accurate to the size of a drop or a bubble, i.e., to approximately 1 mm.

One of the first applications of track detectors was to determine the charge spectrum of the nuclear component of primary cosmic radiation [15, 16]. Studies of the heavy component of primary cosmic rays made use of stacks of nuclear emulsions [17]. The advantages of track detectors as integral instruments accumulating information under conditions of minor particle fluxes were employed not only in balloon experiments but also in satellite experiments with cosmic rays [18]. Stacks of polymer track detectors were subjected to long-time irradiation in a satellite to investigate the energy spectra of cosmic nuclei with the view of obtaining information on nucleosynthesis processes and mean free paths of cosmic nuclei in the interstellar medium [19]. In the 1970s, bubble and spark chambers were the most widespread track detectors [20]. For instance, many properties of strange particles — their mass, lifetime, spin, parity — were determined using these types of detectors [21]. A large number of experiments with chambers studied resonant states of particles and weak interactions [22–25]. Owing to track detectors, many nuclear decays and reactions were discovered, as were new particles (positron, muon, charged pions, strange and charmed particles).

Thus, track detectors have played an outstanding role in the development of nuclear physics due to visualization and the possibility of obtaining an exhaustive spatial pattern of the processes studied. This is confirmed by quite a number of Nobel Prizes in Physics awarded sequentially to:

1903 — A H Becquerel, in recognition of the extraordinary services he has rendered by his discovery of spontaneous radioactivity;

1927 — C T R Wilson, for his method of making the paths of electrically charged particles visible by condensation of vapor;

1936 — V F Hess, for his discovery of cosmic radiation. His apparatus included photoplates and stroboscopes;

1950 — C F Powell, for his development of the photographic method of studying nuclear processes and his discoveries regarding mesons made with this method;

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