Quantum Electronics **33**(7) 609 – 620 (2003)

PACS numbers: 85.60.Ha; 06.60.Jn
DOI: 10.1070/QE2003v033n07ABEH002467

Academician A.M. Prokhorov and femto – attosecond photoelectronics

M.Ya. Schelev

Abstract. **High-speed photography using time-analysing image-converter tubes (ICTs) occupies a worthy place among a variety of scientific fields whose development is closely associated with the name of academician A.M. Prokhorov. It was A.M. Prokhorov who headed in our country from the mid-1960s until the first years of a new century the studies of fundamental processes underlying high-speed image-tube photography. He organised an international cooperation aimed at the development and application of the methods and means for high-speed image-tube diagnostics in laser physics. He provided the conditions for the development of competitive ICTs, diffractometers, and image-converter cameras (ICCs) and for their successful applications in quantum electronics, nonlinear and fibre optics, laser plasma physics, and controlled nuclear fusion. A new scientific field – femto – attosecond photoelectronics was initiated under his influence and is being successfully developed now.**

Keywords: *femto – attosecond laser physics, optics and photoelectronics, time-analysing image-converter tubes, cameras, diffractometers.*

1. Introduction

The story of a high-speed photography began in the XIX century. Two outstanding scientists, a Frenchman E.J. Marey [1] and an Englishman E.J. Maybridge [2] (both 1830 – 1904), invented at this time an optomechanical device for distinct imaging of objects moving at a velocity greatly exceeding the velocity at which a human eye is capable of distinguishing individual phases of such a motion. Being pioneers of high-speed cinematography, they have managed, using an 'electro-photographic imaging', to overcome the time-resolution limit of a human eye ($\sim 10^{-1}$ s) and to obtain a distinct image of separate phases of the motion of human beings and animals with a time resolution of $10^{-2} - 1.7 \times 10^{-4}$ s. At present the time resolution of optomechanical high-speed photography has almost achieved its physical limit ($\sim 10^{-9}$ s), which is determined by the structural strength of the rotating components of optomechanical cameras [3, 4]. It is replaced now by a high-speed videography*, which is based on computer-controlled charge-coupled devices (CCDs). The best ultrafast CCD cameras provide up to one hundred two-dimensional images (312×260 pixels and more) of fast processes at rates exceeding 10^6 frames per second [6].

A real revolution occurred in high-speed photography when our outstanding compatriots E.K. Zavoisky, M.M. Butslov, et al. created and tested the world's first time-analysing image-converter tubes (ICTs) with the time resolution of the order of 10^{-11} s [7]. E.K. Zavoisky and S.D. Fanchenko analysed theoretically the limiting possibilities of time-analysing ICTs [8] and showed that photoelectron methods for recording fast processes offer a unique combination of record parameters. These are a high time resolution (better than 10^{-14} s) and a high spatial resolution (50 – 100 line pairs per mm), an extremely high sensitivity (detection of single photoelectrons), a broad spectral range (0.1 – 1700 nm), a large volume of simultaneously recorded information ($10^6 - 10^8$ pixels), and a broad dynamic range of input intensities (more than 10^5).

Having a remarkable gift for scientific predictions, A.M. Prokhorov (Fig. 1) anticipated the unique detecting properties of time-analysing ICTs and promoted the applications of the methods of image-tube diagnostics in laser experiments. The author of this paper was lucky to work on the solution of this problem under the direct supervision of A.M. Prokhorov from 1962 to 2002.

2. Subnanosecond ICTs at pre-laser times (1928 – 1962)

In the period between 1928 and 1934, when Aleksandr Mikhailovich lived with his parents in Leningrad, studied at a school and then at a work faculty, his foreign contemporaries G. Holst, J.H. Boer, P.T. Farnsworth, et al. [9, 10] proposed for the first time the idea for creation of an image-converter tube and a photomultiplier. It is unlikely that these scientists anticipated at that time the possibility of using their inventions for fast process recording. It was important then to obtain the images of objects in the IR spectral region to solve the problem of night vision. The quality of images produced by the first version of an ICT ('Holst glass' or proximity-focused image tubes) was poor and the spatial resolution was no better than a few line pairs per millimetre. In the 1930s, P.E. Brücher, O.Z. Scherzer, G.A. Morton, V.K. Zworykin, M. Ardene, J.D. McGee, A. Lallemand, et al. [11 – 16]

M.Ya. Schelev A.M. Prokhorov General Physics Institute, Russian Academy of Sciences, ul. Vavilova 38, 119991 Moscow, Russia;
e-mail: schelev@ran.gpi.ru; m.schelev@ran.gpi.ru; tel. 135-32-65;
fax: 135-23-88

Received 29 January 2003; revision received 8 May 2003
Kvantovaya Elektronika **33** (7) 609 – 620 (2003)
Translated by M.N. Sapozhnikov

---

*The modern classification of the methods and devices for high-speed photography is presented in tutorial [5].

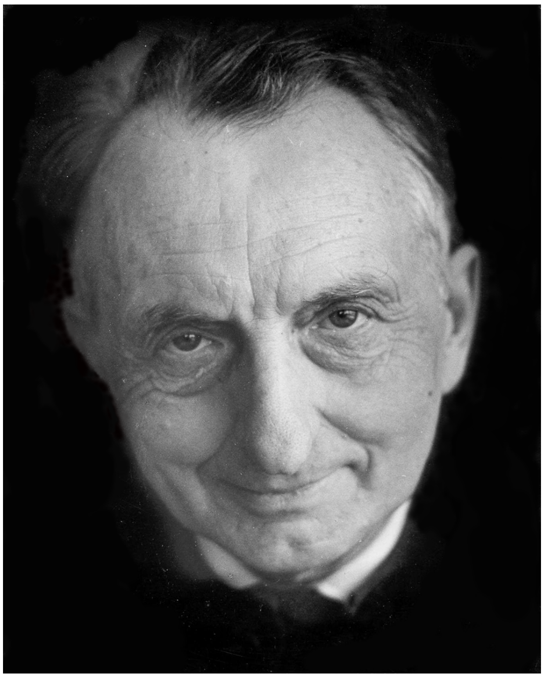

Figure 1. A genius accomplishes what he must accomplish. A talent does what he can. A talent strikes a target that is inaccessible for others. A genius strikes a target that nobody sees.

developed the theory of electrostatic and magnetic lenses. As a result, a variety of different ICTs have been fabricated in Germany, Great Britain, France, and the USA: one-stage and multistage, sensitive in the IR and X-ray spectral ranges, etc. At the same time, AEG-Telefunken manufactured three-electrode electrostatic AEG-126 ICTs, which were the most advanced converters at that time. It is these devices that were used in high-speed photography after the end of the Second World War. For example, in 1949 M.P. Vanyukov [17] from the State Optical Institute (GOI) manufactured a millisecond camera for framing photography using pulsed commutation of an accelerating voltage in such ICTs, while J.S. Courtney-Pratt [18] in Great Britain achieved the sweep of photoelectron images with a nanosecond time resolution by using a pair of magnetic deflection coils fed from a middle-wavelength current generator.

The first proximity-focused ICTs were manufactured in our country in 1938 – 1939 by V.I. Krasovsky, S.Yu. Luk'yanov, et al. at the V.I. Lenin All-Union Electro-Engineering Institute. In the late 1940s, M.M. Butslov and his colleagues developed, based on the theoretical calculations of L.A. Artsimovich [19], a series of one-stage ICTs with the electrostatic image focusing. In these years, M.M. Butslov also performed two technological breakthroughs. He created image intensifiers containing up to six magnetically focused tubes connected in a cascade (via micron-thick mica windows), which provided the ultimate sensitivity (i.e., the ability to detect the minimally detectable signal – a single electron emitted from a photocathode surface). The second breakthrough was the use of deflection plates inside a tube, similar to those employed in an oscilloscope. Indeed, the rate of magnetic deflection of photoelectron images used by J.S. Courtney-Pratt was limited by the inductivity of the deflection coils. However, nobody attempted at that time to deflect an electron beam, carrying a photoelectron image, with the help of rapidly alternating electric fields. Sceptics attempted to persuade Butslov that any deflecting electric field would destroy the photoelectron image. However, encouraged by E.K. Zavoisky, he created a PIO-1 electrostatic ICT having a rather long (several centimetres) crossover (the region of the minimum cross section of a beam carrying a photoelectron image) with a very small diameter (fractions of a millimetre). Butslov placed in the crossover an electronic shutter consisting of two pairs of plates and diaphragms, and two additional pairs of deflection plates behind the shutter. This device was called PIM-3 (Russian abbreviation for 'pulsed multi-frame image-converter'). Later, a time-analysing PIM-3 cascade was coupled via thin mica windows with a magnetically focused multistage image intensifier. As a result, a series of unique time-analysing ICTs of the UMI type (Russian abbreviation of 'pulsed multistage amplifier') was developed, which had no analogues in the world and had a high time resolution (10^{-11} s) and a huge ($10^5 - 10^6$) image intensification gain [7].

E.K. Zavoisky and his team played an outstanding role in the development of the domestic high-speed image-tube instrumentation. They used these new devices in nuclear physics (track detector and subnanosecond counters of nuclear pulses), thermonuclear fusion (low-density plasma spectroscopy, temperature diagnostics, and plasma dynamics), astronomy (almost each contemporary telescope is equipped with an image intensifier), and in optics (even before the invention of lasers). Aleksandr Mikhailovich was well acquainted with Evegenii Konstantinovich and his studies devoted to the development and applications of time-analysing ICTs in nuclear physics.

The most impressive experiment performed by E.K. Zavoisky and his co-workers was the measurement of the ultimate time resolution of an UMI-95 ICT. In 1955 it was very difficult to find light sources emitting ultrashort pulses required for these experiments. E.K. Zavoisky and S.D. Fanchenko decided to record light emitted by an electric discharge in high-pressure nitrogen. Discharges were initiated at frequencies $\sim 10^{10} - 10^{11}$ Hz. The entire emission time of a high-frequency discharge was 200 – 400 ps, whereas the duration of individual light pulses detected in experiments was less than 10 ps. This was indeed the world's first and unique experimental result on the recording of photoelectron images with a picosecond time resolution.

After these successful experiments, E.K. Zavoisky and S.D. Fanchenko began to develop the fundamental principles of pico-femtosecond electro-optical photography. These principles were used for many years for the development and manufacturing of new time-analysing ICTs. In particular, by studying aberrations distorting the image quality, these scientists showed that the first-order temporal chromatic aberration $\delta\tau$ cannot be eliminated in principle and depends on the spread in the initial velocities of photoelectrons, which in turn is determined by the physics of the external photoeffect

$$\delta\tau = mV_{0z}/eE,$$

where m and e are the electron mass and charge, respectively; V_{0z} is the distribution of the initial velocity component of photoelectrons normal to the photocathode; and E is the electric field strength near the photocathode. The latter quantity in a PIM-3 ICT was 300 – 600 V cm^{-1}, corresponding to the minimum value of the chromatic aberration coefficient $\sim 10^{-11}$ s. To eliminate the current overloading of the photocathode and reduce the Coulomb repulsion effects, an image intensifier was used that provided a reliable detection of each single photoelectron emitted by the photocathode. By analysing different mechanisms responsible for imaging in time-analysing ICTs, E.K. Zavoisky and S.D. Fanchenko concluded that the ultimate time resolution of electro-optical chronography may be close to 10 fs.

During the period from 1953 to 1965, many experimental and commercial image-converter cameras (ICCs) for recording fast processes were manufactured in our country. The ultimate time resolution of these cameras was fractions of nanosecond. Domestic PIM – UMI tubes were used in all ICCs. Experimental ICCs were fabricated at I.V. Kurchatov Institute for Atomic Energy (IAE), the State Optical Institute (GOI), the Institute of Physical Problems, and P.N. Lebedev Physics Institute (FIAN). Based on a comprehensive experience accumulated at the IAE, a series of commercial ICTs of the US and LV types was manufactured at the Plant of Electron Microscopes in Sumy town. Experimental cameras based on ICTs of own design [two-electrode (ZIM) and three-electrode (ZIS) with a grid shutter] were developed under the supervision of Yu.E. Nesterikhin at the Novosibirsk Institute of Automation and Electrometry, Siberian Branch, Russian Academy of Sciences. Thus, in our country a unique potential in the development and applications of time-analysing ICTs and cameras was accumulated well before the first laser invention.

3. Mastering the picosecond range: ICTs for lasers and lasers for ICTs (1962-1980)

A number of multifunctional ICCs were developed at the Laboratory of Spectroscopy at FIAN in the period between 1962 and 1969 [20, 21] (Fig. 2). These cameras were specially developed for studies in the fields of laser and plasma physics [22] and surpassed other photoelectron detectors available at that time by featuring a broad temporal detection range (from nanoseconds to milliseconds), the subnanosecond time resolution in a single strak mode, a short triggering delay (~ 20 ns) with jitter less than ±50 ps, and a high sensitivity (the image intensification gain $\sim 10^4 - 10^5$). Such cameras were routinely used in laser studies, providing experimental results that could not be obtained by any other methods. For example, the temporal and spatial parameters of a Q-switched ruby laser were studied with a time resolution better than 0.1 ns at the Laboratory of Luminescence at FIAN (Fig. 3). The dynamics of the far- and near-field laser radiation, the wave-front shape, the space – time coherence, and the spectral and temporal behaviour of laser radiation were also studied [23]. An ICT was used to record the propagation of the ionisation front of a plasma during successive breakdowns in a laser spark in air [24] (Fig. 4). Experimental studies of the self-focusing kinetics in nonlinear liquids with the help of an ICT made it possible to interpret self-focusing filaments as the result of motion of focal points [25].

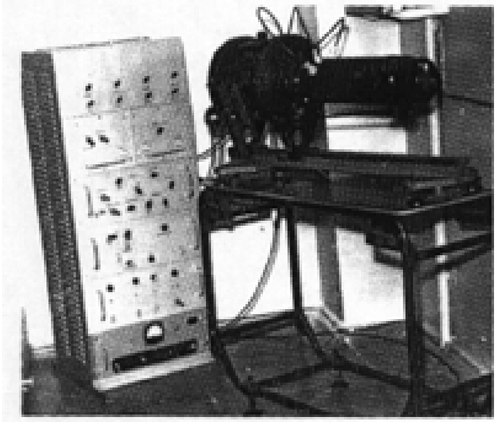

Figure 2. Subnanosecond camera developed on the basis of the UMI-93 ICT.

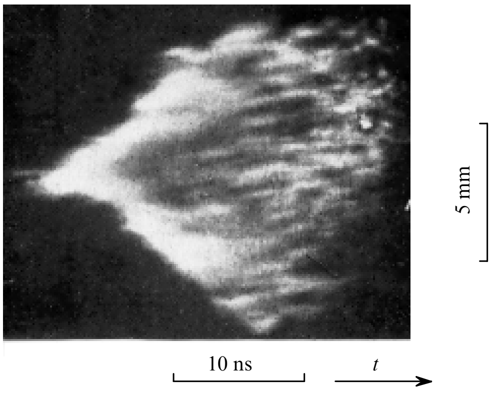

Figure 3. Dynamics of the near-field radiation of a Q-switched ruby laser.

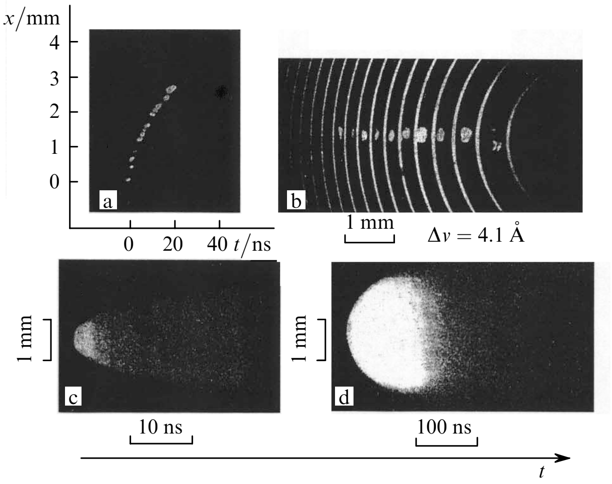

Figure 4. Dynamics of a laser spark appearing upon focusing radiation from a Q-switched ruby laser in air: the photography in reflected laser radiation (a), Doppler shift of reflected laser radiation (b), and the radial propagation of a plasma (c, d).

All these studies, which were performed at the time of the advent of lasers, became the first important investigations in the fields of quantum electronics, nonlinear optics, and laser plasma physics, where the unique possibilities of high-speed photography based on time-analysing ICTs were directly used. During subsequent 35 years from 1967 to 2002 some 250 studies were performed with the participation of A.M. Prokhorov devoted to the development and applications of ICTs in laser experiments.

In 1968, ICTs were modified substantially and their time resolution, determined by the streak speed, achieved 5 ps. As a result, new experimental data were obtained. The fine temporal structure in the radiation of a passively Q-switched mode-locked Nd laser was revealed [26] (Fig. 5). Because the duration of single picosecond pulses was unstable, varying from fractions of picosecond to a few picoseconds over the pulse train period, an experimental test-bench was constructed for dynamic tests of ICTs, which contained a two-frequency Nd laser emitting only two spectral components. To measure the time resolution of ICTs and calibrate the streak speed, a method of mode 'beats' was developed in collaboration with V.V. Korobkin [27, 28] (Fig. 6). This method was widely used in experimental practice until the advent of the first femtosecond laser in the early 1990s.

New data on the dynamics of interaction of high-power picosecond laser pulses with solid-state targets were obtained using ICCs developed at the Laboratory of Spectroscopy at FIAN. These experiments were performed at the Laboratory of Quantum Radiophysics at FIAN by N.G. Basov, O.N. Krokhin, P.G. Kryukov, et al. [29]. At that time the shape and duration of picosecond laser pulses propagating in glass fibres were also experimentally studied for the first time [30]. The dynamics of SBS components in nitrogen at a pressure of 150 atm was studied by I.L. Fabelinskii et al. [31].

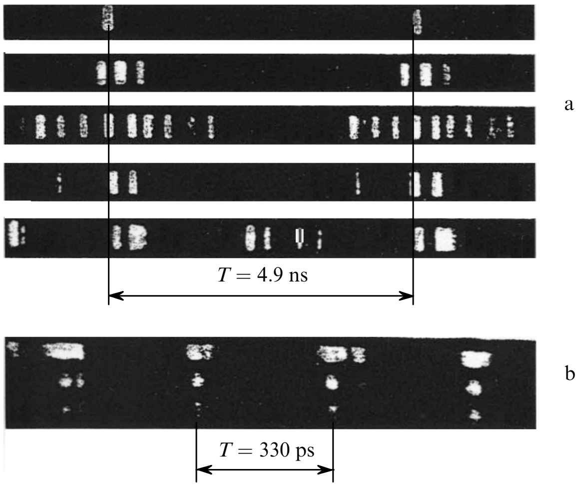

Figure 5. Temporal structure of radiation from a passively mode-locked Nd : glass laser: inside successive axial intervals (a) and the fine temporal structure of radiation inside single axial interval (b).

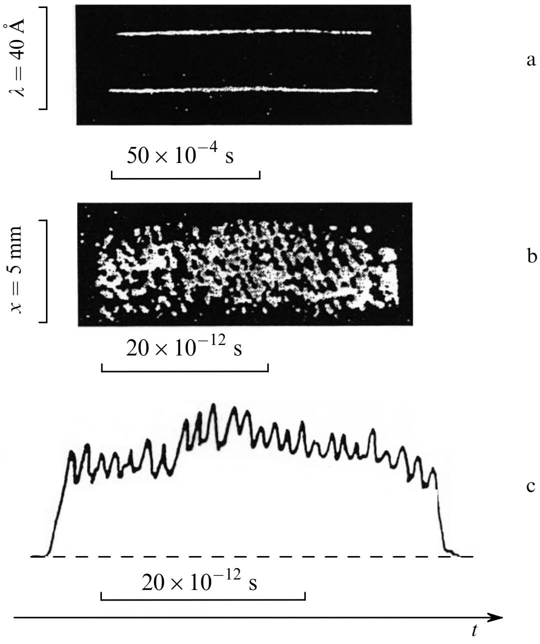

Figure 6. Emission spectrum of a two-frequency Nd : glass laser (a), the corresponding optical beats with the modulation period equal to 1.4 ps (b), and a corresponding microdensitogram trace (c).

Thus, experiments in laser physics performed in the 1960s confirmed the basic principles of high-speed image-tube photography formulated by E.K. Zavoisky and S.D. Fanchenko, and new cameras based on domestic PIM – UMI ICTs with a time resolution of 10 ps were developed. Note that D. Bradley and co-workers in Great Britain [32] independently confirmed these principles using P-856 Photochron streak tubes manufactured by EEV Co. (similar to PIM tubes). During a scientific probation at the National Research Council of Canada (1969 – 1970), the author of this paper also managed in collaboration with J. Alcock and M. Richardson to overcome the 10-ps barrier in laser experiments using the RCA tubes (USA) [33].

In the early 1970s A.M. Prokhorov in cooperation with M.M. Butslov and B.M. Stepanov developed a program aimed at the fabrication of time-analysing ICTs and cameras based on them at the All-Union Research Institute for Optical and Physical Measurements. These devices were intended for laser studies with the time resolution no worse than 1 ps. One of the most outstanding achievements of this well-financed program was the creation of a PV-001 ICT in 1978. Based on this image tube and its modifications, a few hundreds of ICCs [including domestic Agat cameras and Imacon-500 cameras (Great Britain)] have been manufactured and are in use now. Fig. 7 shows an EOK-2M camera developed at FIAN and manufactured at the Design Bureau of Physical Instrument Making in Troitsk. ICTs of the PV type used in EOK-2 and EOK-3 cameras are characterised by a high electric field strength near the photocathode (about of 30 kV cm^{-1}). They have a compensated electronic shutter, one or two symmetric broadband (up to 3 GHz) deflection systems, and an output phosphor screen deposited onto a fibreoptic faceplate. A wide assembly of input widows and photocathodes covers a spectral range from 0.1 to 1600 nm. For experiments on laser controlled thermonuclear fusion, two-component Au – Sb – Cs photocathodes were invented, which are sensitive both in the soft X-ray and visible spectral regions. Using ICTs equipped with such photocathodes, researchers at GOI studied under the supervision of A.A. Mak the dynamics of X-rays emitted by a $(\mathrm{CD}_2)_n$ thermonuclear target irradiated by high-power picosecond laser pulses [34].

The time resolution of the UMI-93M and PV-001 ICTs at a wavelength of 1.06 μm was 0.7 ps for the electric field strength near the photocathode equal to 60 kV cm^{-1} [28], while that of the UMI-93CR ICT at a wavelength of 1 nm was close to 10 ps [35]. The maximum streak speed achieved in these experiments was 5×10^{10} cm s^{-1}, in particular, due

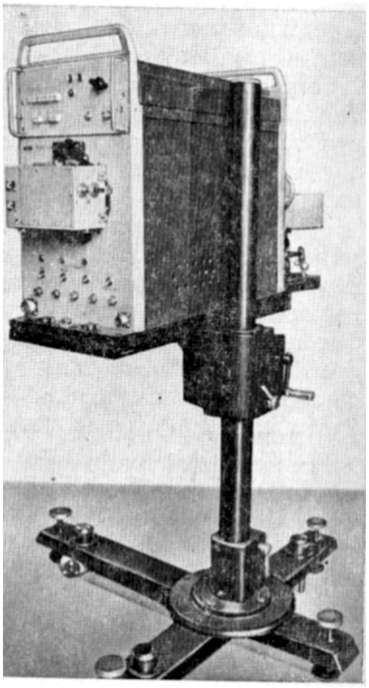

Figure 7. EOK-2M image-converter picosecond camera based on PV-001 and PMU-2V ICTs operating in streak and single-frame modes.

to the use of semiconductor sharpness developed at the Leningrad Physicotechnical Institute [36]. Note that the domestic microchannel plates were used both inside time-analysing tubes and external image intensifiers coupled with a time-analysing ICT via fibreoptic faceplates.

Another remarkable achievement of the 1970s initiated by A.M. Prokhorov is the creation of a picosecond electro-optical informational and measurement system containing a calibration Nd : glass laser, an ICC, and a read-out device based on a SIT vidicon [37]. To improve the quality of images being recorded and to improve the accuracy of quantative measurements, computer software was developed in collaboration with researchers from Moscow State University for the calculation of spatial and temporal instrumental functions of the ICT and their deconvolution upon the estimates of the time and spatial resolution of the ICT [38].

It was pointed out in the greeting from the Academy of Sciences of the USSR in 1980 during the 14th International Congress on High-Speed Photography and Photonics (ICHSPP), which was held for the first time in Moscow, that the studies in the field of picosecond electro-optical photography performed at FIAN under the supervision of A.M. Prokhorov have the world's level.

4. International cooperation in the field of high-speed electro-optical photography (1967 – 2002)

Academician A.M. Prokhorov understood that a real progress in science and technology could not be achieved without an international cooperation and he paid great attention to the development of such cooperation. Thus, from 1972 to 1976, in accordance with the plan of cooperation in the field of science and technology signed by the Soviet-French Commission on Instrument Making, the newest Thomson-CSF picosecond cameras of the TSN type were tested using lasers developed at FIAN. The author of this paper took part in the development of these cameras during probation at CEA, Sacley (1974 – 1975). During cooperative experiments performed at FIAN [39], two methods for recording images from the ICT phosphor screen were investigated: with the help of a multistage UMI-93 image intensifier and a French THX 496 microchannel-plate (MCP) image intensifier. Despite their customs restrictions, Frenchmen decided to bring the MCP image intensifier, however, after A.M. Prokhorov assured that the intensifier would be returned back. It was shown that MCP image intensifiers are promising for using in picosecond cameras employed in laser experiments. In addition, it was concluded that is worthwhile to replace a photographic film by a highly sensitive TV tube with a subsequent recording of images on a video tape recorder and their computer-processing.

The cooperation with the British company DRS-Hadland, which began in 1967, proved to be the most prolonged and fruitful. Aleksandr Mikhailovich was acquainted with the managers of the company J. Hadland, P. Rickett, D. Bowley, et al. and readily met them during their visits to Moscow. The agreement on the cooperative development and fabrication of picosecond ICCs signed at the State Planning Committee of the USSR in 1980 combined the experience for the development of a new generation of PV ICTs accumulated in our country with the experience of the Hadland company in the manufacturing of ICCs for various applications. As a result, an Imacon-500 streak camera was created (Fig. 8). At present more than one hundred of such cameras were fabricated, and all these cameras reliably operate for tens of years in Russia and abroad, providing the recording of fast processes with the time resolution better than 1.5 ps in the spectral range between 110 and 1550 nm [40]. In accordance with the agreement on scientific and technological cooperation between the DRS-Hadland company and the General Physics Institute, RAS (IOFAN), new time-analysing ICTs were developed. The PF tube developed at IOFAN to order of the company was used in a famous British model 468 camera, which was awarded the Royal Prize in the field of high technologies in 1999.

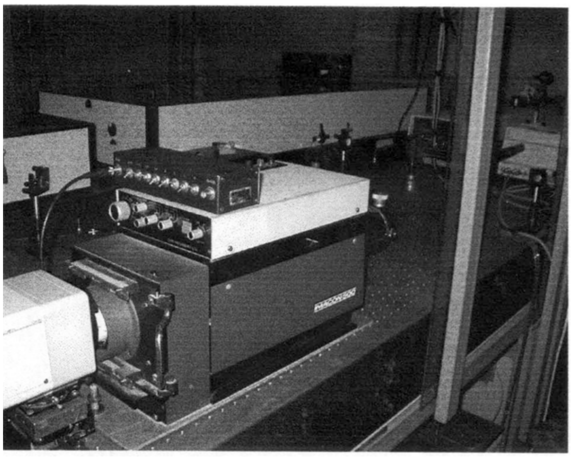

Figure 8. Imacon-500 image-converter camera based on the PV-001 Russian streak tube. The camera was designed and manufactured by DRS-Hadland (Great Britain) in cooperation with FIAN.

A.M. Prokhorov attached particular significance to the cooperation with the Japanese company Hamamatsu. During the most interesting period of this cooperation between 1978 and 1989, the president of the company Teruo Hiruma visited IOFAN every time flying to Europe or America via Moscow. Using domestic PV-001 ICTs and the Japanese C1330 and C1440 TV read-out systems, a picosecond electro-optical information system was jointly developed [41]. Its maximum time resolution was 1.4 ps at a wavelength of 610 nm for a streak speed of 5×10^9 cm s^{-1} and a dynamic detection range of ~ 70. The time-resolved image was transferred from the ICT phosphor screen via a SIT vidicon to a computer in the $256 \times 256 \times 12$ bit format for the data processing and analysis. Unfortunately, an important commercial agreement about the supply of a lot of PV ICTs to Hamamatsu in exchange for the Hamamatsu TV read-out systems, which was signed in 1982 at the Ministry of Foreign Trade of the USSR, was not realised because of the license restrictions for our country.

Another example of a stable and mutually enriching scientific and technological collaboration is the studies performed in cooperation with the American instrument making company CORDIN [42]. Aleksandr Mikhailovich highly estimated the organisation and professional qualities of Sidney Nebeker, the president of CORDIN. The PROSCHEN joint enterprise (English abbreviation of three names Prokhorov, Schelev, and Nebeker) was organised with this company, which existed from 1989 until 1994. Several lots of picosecond ICCs (models 171, 172) were developed and manufactured based on the Russian control circuitries and PV ICTs. The cameras operate in the single streak or synchroscan modes with the scan frequency up to 320 MHz (Fig. 9). In 2002, a universal picosecond camera (model 173) was manufactured by joint efforts, which can operate simultaneously in the streak and synchroscan modes and uses ICTs developed and fabricated at IOFAN.

Figure 9. Synchroscan with a scan rate of 320 MHz based on the PV ICTs designed and manufactured by CORDIN (USA) in cooperation with IOFAN.

In the early 1990s, as a result of the scientific and technical cooperation between the V-TEK company (Korean republic) and IOFAN, which academician A.M. Prokhorov supported with enthusiasm, a PIF (Russian abbreviation of pulsed femtosecond converter) ICT was adapted to the Korean control circuitries. These ICTs were further used in jointly developed experimental ICCs [43]. These cameras provided the time resolution no worse than 10 ps in the single-shot streak mode at the dynamic recording range above 100. For picking up time-displayed images from the phosphor screen a CCD read-out camera was used.

A.M. Prokhorov established collaboration with the Institute of Pure Mechanics and Applied Optics (People's Republic of China). During joint studies, in which H. Niu, V.P. Degtyareva, et al. took part, the results of computer simulations were published and patented for the ICT having a cylindrical electrostatic lens and a compensator of the spread of the initial energies of photoelectrons over the angles of emergence and providing a time resolution of 50 fs [44]. Already the first studies of experimental ICTs with a cylindrical focusing lens (BSHCHV-4) gave encouraging results. Even without a compensator, the time resolution of such an ICT was 500 fs at a wavelength of 1.08 μm for the electric field strength near the photocathode equal to 60 kV cm^{-1} and the streak speed equal to 1.7×10^{10} cm s^{-1} [45].

In the late 1980s, A.M. Prokhorov initiated a series of experiments in cooperation with the Scientific Instrument Making Centre in Berlin (German Democratic Republic) aimed at the development of time-analysing ICTs with a direct read-out of time-displayed images into a computer [46]. The jointly developed ICTs with a built-in silicon target were tested, which was used instead of a luminescent screen. In these experiments, the time-resolved photoelectron image projected on the silicon target was inputted into a computer for fractions of second, retaining a high quality of the image. The idea of a direct reading of images was developed to manufacture a domestic ICT with a built-in CCD array replacing a luminescent screen. For this purpose, a lot of CCD detectors for time-analysing ICTs were fabricated at the Leningrad 'Electron' plant to the order of A.M. Prokhorov [47].

During these years, a femtosecond colliding-pulse R6G dye laser was built at IOFAN in coolaboration with scientists of the Iena University (German Democratic Republic). This laser emitting single 90-fs pulses at 610 nm was used to measure the temporal instumental function of the PV-001 ICT [48]. The mimimal duration of a photoelectron pulse recorded on the ICT phosphor screen was 900 fs. When the photocathod was irradiated by 1.15-μm 500-fs pulses from a solid-state $F_2^- : \mathrm{LiF}$ colour centre laser [49], the time response of the ICT narrowed down to 700 fs. In these two experiments, an Ag–O–Cs photocathode was used, the electric field strength was 30 kV cm^{-1} and the streak speed was $(1.6-2) \times 10^{10}$ cm s^{-1}. The image was transferred from the ICT phosphor screen via an MCP image intensifier (with the gain of 3×10^4) to an extremely sensitive TV read-out system.

Note that the late 1980s and early 1990s were the period of the most active international scientific and technical collaboration for IOFAN in the field of ultrahigh-speed electro-optical instrument making. For example, at this time new picosecond ICCs with a circular streak were developed in cooperation with the Prague Technical University (Czechoslovakia) and successfully used for laser probing of the atmosphere [50]. A 1.55-μm erbium-doped fibre laser intended for ultra-broadband fibreoptic communications [51] was jointly studied at the University Campinas (Brazil) using picosecond EOK-2 and EOK-3 cameras developed at IOFAN.

Figure 10. A.M. Prokhorov among delegates of the 23th International Congress on High-speed Photography and Photonics, Moscow, FIAN, 1998.

A high level of domestic studies in the field of ultrahigh-speed electro-optical diagnostics was acknowledged by the successive 23d ICHSPP, which was held at FIAN in Moscow in 1998. Academician A.M. Prokhorov was the president of the congress (Fig. 10).

5. Femtosecond image-tube technologies en route (1980-2002)

The femtosecond temporal range was mastered under less favourable conditions than, for example, during the previous decade. The period of organisation demolishing began and the existing tempo of scientific studies was lost. At this critical moment, A.M. Prokhorov came to an extraordinary decision: to develope and manufacture experimental time-analysing ICTs at IOFAN. For this purpose, he decided to build up his own scientific and technological chain with a complete and closed cycle – from theoretical calculations, via the fabrication of experimental devices and their dynamic testing, to the application of these devices in physical experiments. Contrary to many opponents of this idea, including his co-workers, Aleksandr Mikhailovich realises this task step by step. First of all, he strengthens the corresponding sections of IOFAN. Thus, the sector of picosecond photonics, which was created in 1982 at the laboratory of P.P. Pashinin and was headed by the author of this paper, was transformed to a laboratory and, finally, to the Department of Photoelectronics in 1989. Moreover, Aleksandr Mikhailovich received a permission of the Academy of Sciences of the USSR and the State Committee of Standards to form a temporary creative collective 'Femtophot' based on the B-4 laboratory headed by G.I. Bryukhnevich at the All-Union Research Institute for Optical and Physical Measurements and the Department of Photoelectronics at IOFAN. The main task of the 'Femtophot' team was to prevent the destruction of the scientific, technological, and personnel potential accumulated in the field of electro-vacuum technologies and electro-optical scientific instrumentation.

Using his enormous scientific authority, A.M. Prokhorov achieved the financing to purchase specialised vacuum and analytic equipment (three-chamber Riber unit) and domestic molecular-beam epitaxy units Shtat and Tsna-9. Using this unique equipment, photocathodes for time-analysing ICTs were fabricated on the basis of Schottky-barrier InGaAs/InP/Ag(Au) structures grown at the Department of Photoelectronics. The sensitivity of these photocathodes was two orders of magnitude higher that that of the best Ag – O – Cs photocathodes at a wavelength of 1.55 μm [52]. The method of molecular-beam epitaxy also gave excellent results in the growing of conventional multi-alkali photocathodes: the quantum efficiency at a wavelength of 400 nm was 40 %, the spectral characteristic being well reproducible [53].

As a whole, in the 1980s a closed research and technological chain was created at IOFAN for computer simulations, design and dynamic tests of the experimental samples of femtosecond ICTs, femtosecond photoelectron guns and cameras on own laser test-benches [54] (Fig. 11). Ultrahigh-speed photoelectron devices (Fig. 12) that are being developed and manufactured at present at IOFAN are competitive at the world market. These include time-analysing PIF and PF ICTs of the original design and modernised PV ICTs [55]. They have the following parameters: the size of the working region of photocathodes is between 6 and 20 mm, the spatial resolution with respect to the plane of the input photocathode is 30 – 50 line pairs per mm, the spectral sensitivity range is 0.1 – 1600 nm, and the equivalent level of the dark background is no more than 10^{-6} lm cm^{-2}. A pulse voltage applied between the photocathode and the accelerating grid provides the increase in the electric field strength near the photocathode surface up to 300 kV cm^{-1}, which ensures the time resolution better than 100 fs.

The advent at the early 1990s of Ti : sapphire lasers emitting stable single femtosecond pulses [56] facilitated the development of direct image-tube methods of diagnostics of fast processes with the femtosecond time resolution.

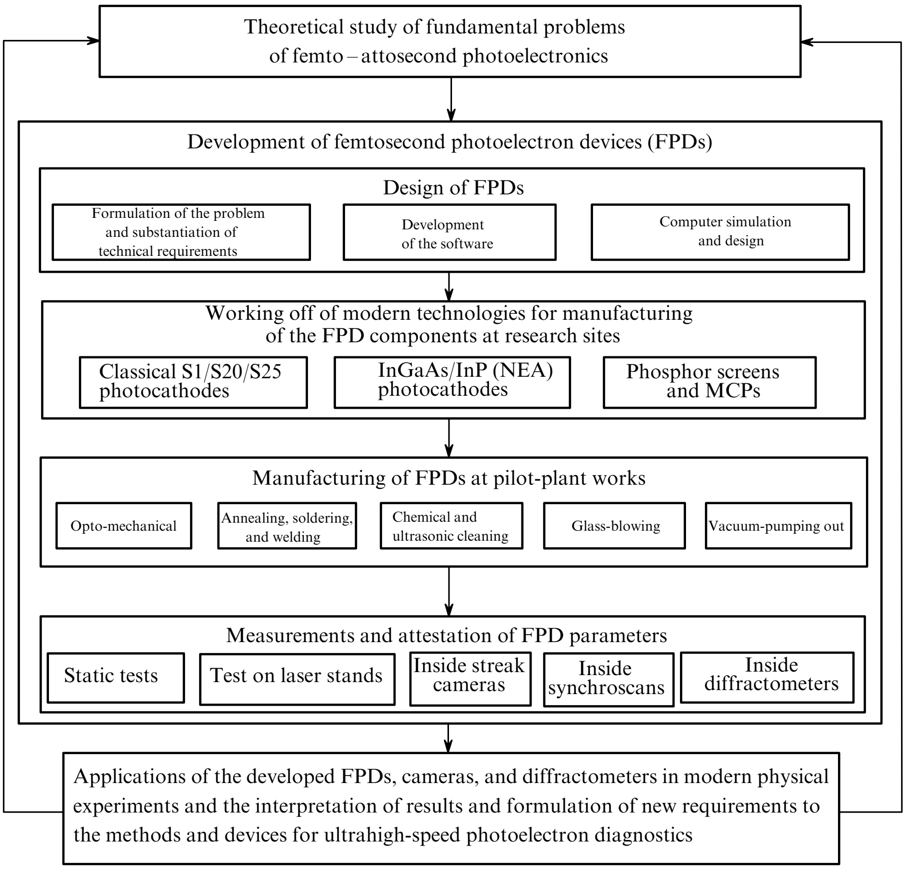

Figure 11. Block diagram of the research and technological chain for design, development and manufacturing of femtosecond ICTs, cameras, and diffractometers (Department of Photoelectronics, IOFAN).

In 1995, a femtosecond laser setup was built at the Department of Photoelectronics at IOFAN for measuring the dynamic parameters of ICTs, cameras, and diffractometers. A Kerr-lens self-mode-locked Ti : sapphire laser was used as a master oscillator. It was pumped by the second harmonic of a diode-pumped Nd : YVO_4 laser. The master oscillator emitted 60-fs single pulses with a pulse repetition rate of 82 MHz, a maximum average power of 0.6 W, and a peak pulse energy of 5 – 7 nJ. The use of a regenerative amplifier operating at a pulse repetition rate of 10 Hz provided the maximum peak energy of 120-fs pulses up to 1.5 – 1.8 mJ.

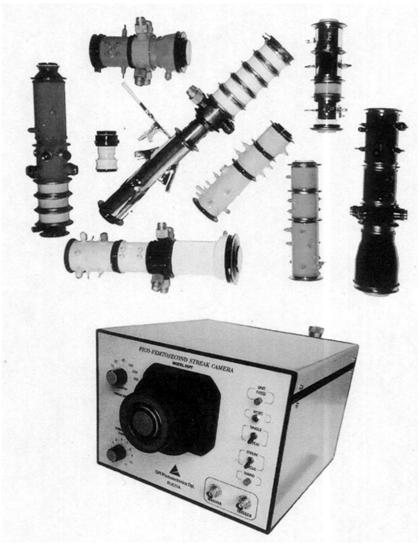

Figure 12. Pico – femtosecond ICTs, photoelectron guns, and cameras developed and manufactured at the Department of Photoelectronics at IOFAN.

A.M. Prokhorov initiated in the late 1990s the studies on the development of femtosecond ICTs of the PV-FS type with a pulsed feeding of the photocathode-accelerating mesh gap, an enhanced sensitivity and a broad transmission band of a deflecting system. The dynamic tests of the experimental samples of PV-FS ICTs with the help of the femtosecond laser setup are described below. We discussed the results of these tests with Aleksandr Mikhailovich many times during 2001, and they are published in our last joint paper [57].

A laser beam of diameter 3 – 5 mm illuminates a variable (with an accuracy of 1 μm) mechanical slit, whose image is projected on an input photocathode of diameter 6 mm by an optical system consisting of two photographic Gelios-44 objective lens and a set of neutral and colour filters. According to calculations, after the propagation of incident pulses through the optical system (a total thickness of glass in the system was no less than 150 mm), their duration increased up to 230 fs if the pulses came from the master oscillator and up to 160 fs if they came from the regenerative amplifier. The through spatial resolution of the entire system (ICT + MCP + CCD camera) with respect to the photocathode was no worse than 30 line pairs per mm. The Ag – O – Cs photocathodes used in these ICTs provided the recording of optical images in the range from 115 to 1550 nm.

The electric field strength near the photocathode surface in these experiments was 130 kV cm^{-1}. Laser radiation from the output of the regenerative amplifier was incident on the entrance slit of the 30-μm width. Time-resolved images were projected from the ICT phosphor screen onto the CCD array through the MCP image intensifier with a gain of 3×10^4. For the electro-optical magnification of 2.8, the half-width of the entrance slit on the ICT screen was ~ 100 μm.

Fig. 13 shows a typical single laser pulse recorded on the ICT phosphor screen. The image is curved because of the difference in the flying times of electrons near the axis and at the periphery. These data are additionally used to calibrate exactly the streak speed. The FWHM of the detected photoelectron pulses was 240 ± 40 fs and depended on the position of the integration window. This means that the time resolution of PV-FS tubes measured at the streak speed of 5×10^{10} cm s^{-1} after deconvolution of the ICT instrumental function is no worse than 200 fs.

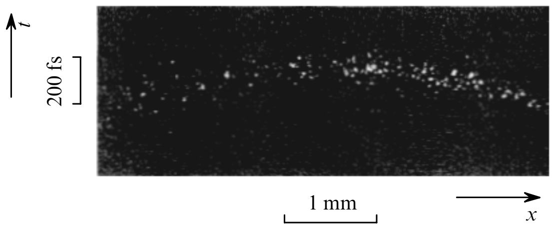

Figure 13. Slit scan of the photoelectron image produced by a single 160-fs pulse from a Ti : sapphire laser. The streak speed is 5×10^{10} cm s^{-1}, the electric field strength near the ICT photocathode is 1.3×10^7 V m^{-1}.

The 1990s are characterised by active investigations in the field of photoelectron diffractometry [58]. In 1991, A. Zewail [59] proposed to us to develop a source of femtosecond 30 – 50-keV photoelectron bunches for time-resolved electron diffraction (TRED) experiments. A.M. Prokhorov blessed this proposal, and already after a few months we built a photoelectron gun based on the electron optics of the PV-001 ICT, which formed electron bunches of duration less than 700 fs. During a few following years, within the framework of the ISTC Project Nos 037 and 1280 supported by A.M. Prokhorov, we developed, fabricated, and tested a gun emitting 30-keV, 250-fs electron bunches.

The principal scheme for TRED experiments allowing the study of the atomic and molecular dynamics in solids and gases is as follows. Femtosecond laser pulses act on a substance under study and, depending on its physical structure, stimulate fast processes such as the heating of a crystalline lattice, phase transitions, chemical reactions, etc. A probe electron beam with the appropriate energy, angular divergence, and duration 'illuminates' but not disturbs the excited substance at instants shifted with respect to the instant of the laser pulse action. As a result, a sequence of diffraction images is formed, which is locked to a certain time phase of the process under study. Figure 14 shows the example of a diffraction image obtained in 1995 upon the interaction of 500-fs, 30-keV electron beams with a 300-Å thick aluminium target in the 'transmission' mode [60].

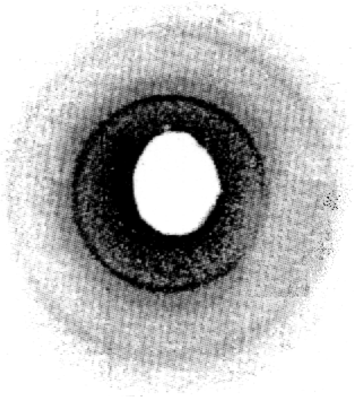

Figure 14. Diffraction image obtained upon irradiation of 300-Å thick aluminium target in the 'transmission' mode by 500-fs, 30-keV photoelectron beams.

The results of these experiments were highly appreciated by the then future Nobel Prize laureate professor A. Zewail. However, the studies on femtosecond electron diffraction should be further developed, and the photoelectron-beam duration should be shortened at least by an order of magnitude.

6. Femto – attosecond photoelectronics – a new branch of science (2000 – our time)

Thus, owing to the efforts of academician A.M. Prokhorov and his school, a new interdisciplinary direction of studies in modern experimental physics was formed by the early XXI century – femto – attosecond photoelectronics. Today this direction includes the investigation of spectral, spatial and temporal parameters of external photoeffect, the development of photocathodes of a classical type and with a negative electron affinity, theoretical electron optics and computer simulation of focusing lenses for time-analysing ICTs and photoelectron guns, the physics of femtosecond lasers and their application in high-speed photography, electro-vacuum technologies and electro-optical instrument making, as well as the problems of reading and digital processing of time-resolved photoelectron images.

A reasonable question arises: When all this forty-year reserve of studies and developments can be realised in devices for photographing fast processes with the required femtosecond (visible and IR lasers) and attosecond (X-rays) time resolution? Concerning such a formulation of the problem, we should again return to the conclusions made by E.K. Zavoisky and his co-workers fifty years ago. They predicted (which was later confirmed experimentally many times) that, to achieve a time resolution of 10 fs, it is necessary to increase the electric field strength near the photocathode surface up to $3 \times 10^5 - 10^6$ V cm^{-1}, to decrease the energy spread of electrons down to 0.05 – 0.1 eV, to increase the streak speed up to $(1 - 3) \times 10^{11}$ cm s^{-1}, to increase in hundred times the signal-to-noise ratio during the scan, to decrease the effect of Coulomb repulsion inside a photoelectron bunch carrying an image, etc. It is also necessary to optimise simultaneously the parameters of all elements of a detecting chain: an optical system projecting the image of the ultrafast event onto the input photocathode, a time-analysing ICT and an image intensifier, pulsed subnanosecond schemes for controlling photoelectron images in ICTs, as well as of the computer hardware and software. By overcoming great engineering problems encountered in the development of femtosecond ICTs, cameras, and diffractometers, their time resolution was improved during the last quarter of the century (1976–2002) only by a factor of 3–5 (from 700 down to 100–200 fs, depending on the virtuosity of experimenters). Moreover, such a 'head-on attack' (increasing the electric field strength near the photocathode, increasing the streak speed, etc.) promises a possible improvement in the time resolution only by an order of magnitude. What to do further and where to direct efforts?

The intense discussions of this problem with A.M. Prokhorov during 2000–2001 facilitated its solution. The essence of the solution consists in the development of an absolutely new generation of time-analysing ICTs in which, along with a conventional electromagnetic lens for spatial focusing of photoelectron images, an additional lens is used for temporal focusing of photoelectron images.

The principal possibility of a spatial and temporal focusing of electron beams in nonstationary (for example, time-periodic) electromagnetic fields is well known and is widely used in microwave devices with continuous electron beams (such as klystron, magnetron, etc.) and in some time-of-flight mass analysers. The possibility of spatial and temporal focusing of photoelectron beams in time-dependent electromagnetic fields was discussed beginning from the mid-1990s [61]; however, the theoretical foundations applied to femtosecond photoelectronics were not developed.

Aleksandr Mikhailovich approved and supported with enthusiasm the idea of using rapidly varying electric fields for temporal focusing to provide the subfemtosecond dynamic compression of electron beams during their motion inside a vacuum tube. It is very important that such an approach does not require extremely high electric field strengths near the photocathode surface. M.A. Monastyrskii with co-workers from his laboratory studied theoretically this idea and developed the software for a precision computer simulation of the dynamics of ultrashort photoelectron beams in nonstationary fields. A simple model was proposed which illustrates the possibility of the first-order temporal focusing in quasi-stationary electric fields [62]. A quasi-stationary hyperbolic mirror was chosen, whose axial potential can be written in the form

$$\Phi(t,z) = \Lambda tz - C\frac{z^2}{2},$$

where t is the time; z is the axial coordinate; and Λ and C are positive constants.

Fig. 15 shows the axial movement of electrons with different initial energies from the initial instant $t_0 = 0$. Even for a comparatively large spread in the initial energies of electrons from 0 to 500 eV (this range is taken for clarity of the figure), the two first temporal foci of an electron beam are distinctly observed. The first-order temporal focusing with the help of a quasi-stationary hyperbolic mirror cannot be substantially distorted by a large spread in the initial energy of electrons because a time-dependent electric field focuses not only the electrons with different initial energies flying out simultaneously but also the electrons flying out at different instants. An electric field varying along the axis focuses the low initial-energy electrons to a greater extent than the high-initial energy electrons. This concerns to some degree the effect of Coulomb repulsion between electrons inside an electron bunch.

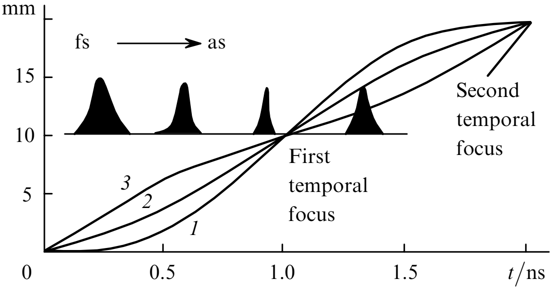

Figure 15. Results of computer simulation of the temporal focusing of photoelectron packets in nonstationary electric fields for initial photoelectron energies equal to 0 (*1*), 100 (*2*), and 500 eV (*3*).

One of the variants of a computer model of a femto–attosecond ICT, where the temporal and spatial focusing of photoelectron images is performed simultaneously, is shown in Fig. 16. The calculations show that, for the experimentally accessible rates of variation in the focusing potential applied to a 'time lens' (above 10 kV ns^{-1}), a 500-fs photoelectron beam with the electron energy spread ~ 0.3 eV can be compressed down to 20 fs. In principle, under certain conditions, which are dictated first of all by the experimentally accessible rate of variation in the focusing electric field, the temporal compression can achieve a few femtoseconds or even fractions of femtosecond. As for the ultimate rate of data transfer using a photoelectron beam, we still have an enormous reserve because the frequency pass band of a photoelectron circuit in an ICT, which is determined by the de Broglie wavelength of the 20–30-keV electrons, is less than 10^{-2} nm, which provides in the limit the data transfer with the subattosecond time resolution ($10^{-19} - 10^{-20}$ s).

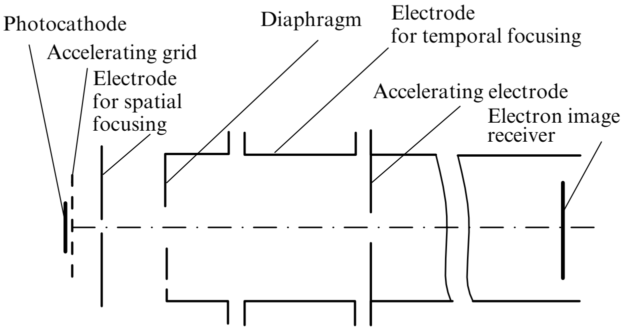

Figure 16. Computer model of a focusing lens providing simultaneously the spatial and temporal focusing of photoelectron images.

These estimates demonstrate the inexhaustible possibilities of ultrahigh-speed photoelectronics and show that the scope of investigations in this field is sufficient for more than one generation of researchers.

7. Instead of conclusion

28 December 2001 we discussed again with Aleksandr Mikhailovich in his office the current problems of ultrahigh-speed photoelectronics. In particular, we talked about the necessity of using a 'pure' room for assembling ICTs

and, in this connection, about a possible increase of the electric field strength near the photocathode. He promised to bring an article from his home, in which the problems of formation of attosecond electromagnetic pulses were considered. He wanted to call to the Ministry of Industry and Science to say that the Ministry should include the relevant studies performed at IOFAN to the interdepartmental program on femtosecond technologies. We discussed the preparation of his article for publication in 'The Herald of Russian Academy of Sciences' [63], in which he wanted to attract the attention of the RAS management to the necessity of the development of own instrumental basis using the unique devices and scientific technologies created in the Academy itself... Obviously, it was not enough time for solving all these problems, but the new 2002 year was ahead, and we decided to meet again at the very first working days in January. But it was at the first working day of 2002, 8 January, that A.M. Prokhorov passed away.

All those who worked directly under the supervision of Aleksandr Mikhailovich or in a close contact with him and those who simply knew him or heard of him remember with deep respect academician A.M. Prokhorov – a great Teacher and a wonderful Man [64]. Forty years ago, owing to his outstanding erudition and sophisticated scientific feeling, he understood that ICTs offer considerable promise for applications in laser experiments. The correctness of this conclusion became evident when only ICTs made it possible to photograph the spatial and temporal structure of laser radiation and laser-induced fast processes with the pico-femtosecond time resolution. By supporting the development of this direction by his creative participation, financing, personnel, young scientists, etc., A.M. Prokhorov promoted the development of a new scientific field – femto–attosecond photoelectronics. Let the new advances in this field be devoted to his memory.

Acknowledgements. The author thanks K.A. Prokhorov, Yu.E. Nesterenkhin, I.A. Shcherbakov, P.P. Pashinin, A.A. Manenkov, G.N. Mikhailova, N.A. Irisova, as well as G.I. Bryukhnevich, V.P. Degtyareva, M.A. Monastyrski, V.A. Tarasov, I.M. Scheleva, and E.A. Kuz'menko for their advice and help in the preparation of this paper.

References

1. Marey E.J. *Scientific American*, 19 October (1878).
2. Maybridge E.J., in *Animal Locomotion, an Electrophotographic Investigation of Consecutive Phases of Animal Movement* (Philadelphia: J.B. Lippincott and Co, 1887).
3. Schardin H. *Proc. 3-d Intern. Congr. High-Speed Photogr. (ICHSPP)* (London, 1956) p. 316.
4. Shnirman G.L., in *Uspekhi nauchnoi fotografii* (Advances in Scientific Photography (Moscow: Nauka, 1959) Vol. 6, p. 93.
5. Andreev A.N., Dubovik A.S., Degtyareva V.P., Monastyrskii M.A., Schelev M.Ya. *Vysokoskorostnaya fotografiya i fotonika v issledovanii bystroprotekayushchikh protsessov* (High-speed Photography and Photonics in the Studies of Fast Processes) Ed. by A.M. Prokhorov (Moscow: Logos, 2002) p. 458.
6. Kondo Ya. et al. *Conf. Dig. 25th ICHSPP* (Beaune, France, 2002) p. 6.
7. Butslov M.M., in *Uspekhi nauchnoi fotografii* (Advances of Scientific Photography) (Moscow: Nauka, 1959) Vol. 6, p. 76.
8. Zavoisky E.K., Fanchenko S.D. *Dokl. Akad. Nauk SSSR*, **100**, 661 (1955); *Dokl. Akad. Nauk SSSR*, **108**, 218 (1956); *Appl. Opt.*, **4**, 1155 (1965); *Preprint of Institute for Atomic Energy 'High-speed Photography with the* $10^{-9}-10^{-14}$*-s Exposures Based on ICTs'* (Moscow, 1966); *Dokl. Akad. Nauk SSSR*, **226**, 1062 (1976).
9. Holst G., de Boer J.H., Teves M.C., Vennemans C.F. *Physica*, **1**, 297 (1934).
10. Farnsworth P.T. US Patent 1969399 (1930).
11. Brüche P.E., Henneberg W. *Ergebnisse der exacten Naturwissenschaften*, **15**, 365 (1936); *Koll. Zeits*, **100**, 192 (1942).
12. Scherzer O.Z. *Phys.*, **101**, 593 (1936).
13. Zvorykin V.K., Morton G.A. *Opt. J. Soc. Am.*, **26**, 181 (1936).
14. Ardene M. *Elektr. Nachr. Techn.*, **13**, 230 (1936).
15. Mc Gee J.D. British Patent 504927 (1937).
16. Lallemand A. *Compt. Rend.*, **203**, 243 (1936).
17. Vanyukov M.P., Nilov E.V. *Zh. Tekh. Fiz.*, **24**, 1209 (1954).
18. Courtney-Pratt J.S. *Research, Suppl.*, **2**, 287 (1949); *Photogr. J.*, **92 B**, 137 (1952).
19. Artsimovich L.A. *Izv. Akad. Nauk SSSR, Ser. Fiz.*, **8**, 313 (1944).
20. Schelev M.Ya. *Ustanovka dlya registratsii bystroprotekayushchikh protsessov* (Setup for Recording Fast Processes) (Radioengineering Diploma, Moscow, FIAN, 1962).
21. Malyavkin L.P., Korobkin V.V., Schelev M.Ya. *Prib. Tekh. Eksp.*, (4), 129 (1965); *Prib. Tekh. Eksp.*, (6), 214 (1968).
22. Korobkin V.V., Malyutin A.A., Schelev M.Ya. *J. Photogr. Science*, **17** (5), 179 (1969).
23. Korobkin V.V., Leontovich A.M., et al. *Pis'ma Zh. Eksp. Teor. Fiz.*, **3**, 301 (1966).
24. Korobkin V.V., Mandelshtam S.L., Prokhorov A.M., et al. *Zh. Eksp. Teor. Fiz.*, **53**, 116 (1967).
25. Butenin A.V., Korobkin V.V., et al. *Pis'ma Zh. Eksp. Teor. Fiz.*, **6**, 687 (1967); Korobkin V.V., Prokhorov A.M., et al. *Pis'ma Zh. Eksp. Teor. Fiz.*, **11**, 153 (1970).
26. Malyutin A.A., Schelev M.Ya. *Pis'ma Zh. Eksp. Teor. Fiz.*, **9**, 445 (1969); *J. SMPTE*, **79**, 35 (1970).
27. Korobkin V.V., Schelev M.Ya. *Zh. Eksp. Teor. Fiz.*, **53**, 1230 (1967); *Zh. Tekh. Fiz.*, **38**, 497 (1968).
28. Bryukhnevich G.I. et al. *Pis'ma Zh. Eksp. Teor. Fiz.*, **2**, 1009 (1976).
29. Basov N.G., Krokhin A.N., Kryukov P.G., et al. *Kvantovaya Elektron.*, (1), 4 (1971) [*Sov. J. Quantum Electron.*, **1** (1), 2 (1971)]; *Proc. 9th Int. Conf. on Ionized Gases* (Bucharest, 1969) p. 330; *Kratk. Soobshch. Fiz. FIAN*, **8**, 48 (1970); *Preprint FIAN* (60) (1970).
30. Vul'fson K.S., Kazachkov V.G., Malyutin A.A., et al. *Svetotekh.*, **6**, 8 (1969).
31. Korobkin V.V., Mash D.I., Fabelinskii I.L., et al. *Pis'ma Zh. Eksp. Teor. Fiz.*, **5**, 372 (1967).
32. Bradley D.J. *J. Phys. Chem.*, **82**, 2259 (1978).
33. Schelev M.Ya., Richardson M.C., Alcock A.J. *Appl. Phys. Lett.*, **18** (8), 354 (1971).
34. Borodin V.G. et al. *Abstracts of Papers, 7th Conf. on Coherent and Nonlinear Optics* (Tbilisi: Metsniereba, 1976) Vol. 2, p. 243.
35. Bryukhnevich G.I., Richardson M.C., et al. *Phys. Lett. A*, **51** (4), 249 (1975).
36. Grekhov I.V., Kardo-Sysoev A.F., et al., in *Proc. of the 14-th ICHSPP* (Moscow: VNIIOFI, 1980) p. 222.
37. Schelev M.Ya. *Proc. SPIE Int. Soc. Opt. Eng.*, **189**, 142 (1978).
38. Platonov V.N. et al. *Proc. SPIE Int. Soc. Opt. Eng.*, **97**, 552 (1976).
39. Jean-Francois G. et al., in *Proc. of the 11-th ICHSPP* (London: Chapman and Hall, 1974) p. 190; *Prib. Tekh. Eksp.*, (1), 254 (1975).
40. Prokhorov A.M., Hadland J., et al., in *Proc. of the 14-th ICHSPP* (Moscow: VNIIOFI, 1980) p. 124.
41. Prokhorov A.M. et al. *Trudy FIAN*, **155**, 233 (1985); Hiruma T., Prokhorov A.M., et al. *Proc. SPIE Int. Soc. Opt. Eng.*, **348**, 206 (1982).
42. Prokhorov A.M., Nebeker S.J., et al. *Laser Focus World*, February, 85 (1989); *Laser Focus World*, December, 125 (1991).
43. Prokhorov A.M., Lozovoi V.I., et al. *Proc. SPIE Int. Soc. Opt. Eng.*, **1801**, 233 (1992).
44. Degtyareva V.P., Niu H., Prokhorov A.M., et al. *Proc. SPIE Int. Soc. Opt. Eng.*, **1032**, 79 (1988).

45. Babushkin A.V., Bryukhnevich G.I., Degtyareva V.P. *Proc. SPIE Int. Soc. Opt. Eng.*, **1801**, 218 (1992).
46. Babushkin A.V. et al. *Proc. SPIE Int. Soc. Opt. Eng.*, **1032**, 75 (1988).
47. Dalinenko I.N., Prokhorov A.M., et al. *Proc. SPIE Int. Soc. Opt. Eng.*, **1243**, 87 (1990); *Proc. SPIE Int. Soc. Opt. Eng.*, **1358**, 739 (1990).
48. Vorobiev N.S., Degtyareva V.P., Prokhorov A.M., et al. *Proc. SPIE Int. Soc. Opt. Eng.*, **793**, 185 (1987).
49. Babushkin A.V., Basiev T.T., et al. *Kvantovaya Elektron.*, **13**, 2262 (1986) [*Sov. J. Quantum Electron.,* **16**, 1492 (1986)].
50. Hamal K. et al. *Rev. Sci. Instrum.*, **50** (3), 337 (1979).
51. De Souza E.A., Prokhorov A.M., et al. *Proc. SPIE Int. Soc. Opt. Eng.*, **1358**, 556 (1990).
52. Nolle E.L., Prokhorov A.M., Schelev M.Ya. *Dokl. Ros. Akad. Nauk*, **348**, 45 (1996).
53. Chernikov A.S. et al. *Proc. SPIE Int. Soc. Opt. Eng.*, **1358**, 134 (1990).
54. Degtyareva V.P., Prokhorov A.M., et al. *Proc. SPIE Int. Soc. Opt. Eng.*, **2869**, 112 (1996).
55. Schelev M.Ya. *Usp. Fiz. Nauk*, **170**, 1002 (2000); *Kvantovaya Elektron.*, **31**, 477 (2001) [*Quantum Electron.*, **31**, 477 (2001)].
56. Kryukov P.G. *Kvantovaya Elektron.*, **31**, 95 (2001) [*Quantum Electron.*, **31**, 95 (2001)].
57. Prokhorov A.M. et al. *Kvantovaya Elektron.*, **32**, 283 (2002) [*Quantum Electron.*, **32**, 283 (2002)].
58. Mourou G., Williamson S., et al. *Proc. SPIE Int. Soc. Opt. Eng.*, **348**, 313 (1982); *Appl. Phys. Lett.*, **41** (1), 44 (1982).
59. Zewail A.H. *J. Phys. Chem.*, **100**, 12701 (1996); *Letters to Nature*, **386**, 159 (1997); *Science*, **242** (4886), 1645 (1988).
60. Prokhorov A.M. et al. *Opt. Engng,* **37** (8), 2249 (1998).
61. Vartak S.D., Lawandy N.M. *Opt. Commun.*, **120**, 184 (1995).
62. Monastyrski M.A. et al. *Conf. Dig. 25-th ICHSPP* (Beaune, France, 2002, p. 57).
63. Prokhorov A.M. *Herald of the RAS*, **73** (6), 483 (2003).
64. Prokhorova G.A. *Luch nadezhdy* (Ray of Hope) (Moscow: FIAN, 2001).