control of the process are done by a commercially available computer, which makes the operation of the facility more reliable.

The facility is also shipped to other countries. At present, a production prototype (based on the above-described facility) that will be used for local dynamic shaping is being built. Another production prototype will be fabricated to ensure three-dimensional control of the crystal shape in the growth process.

3. The main areas of development of the Experimental Factory of Scientific Engineering (EFSE) of the Russian Academy of Sciences

Today the main areas of the EFSE practical activities are as follows:

(1) the production of modern telecommunications equipment;

(2) the design and production of modern engineering facilities for automated systems used in controlling technological processes, facilities for use in industrial and special purpose electronics, and HSCs for industrial units, including atomic power stations;

(3) the design and production of automated facilities for single-crystal growth and of analytical instruments for studying the structure and chemically analyzing substances, and

(4) the design and production of facilities for special projects.

Work to launch serial production of telecommunications equipment of plesiochronous digital hierarchy (PDH) and synchronous digital hierarchy (SDH) began in 1994. The equipment of NEC Corporation (Japan) was taken as the basic equipment. In 1997, EFSE bought the technology and licence from NEC to produce on its own the above equipment. Since April 1998, EFSE has been producing telecommunications equipment of PDH and SDH according to a complete manufacturing cycle. In 1999, EFSE commercially produced SDH equipment of the STM-16 level with a data transmission rate of 2500 Mbps. Several dozen Russian communications companies, among which are the biggest companies such as RosTeleKom and the St. Petersburg Telephone Company, the Russian Ministry of Transportation, and the Moscow Region Elektrosvyaz' Company have become EFSE's clients.

The RAS Experimental Factory of Scientific Engineering is the first Russian plant to master the production of SDH equipment. The equipment produced by EFSE and NEC and shipped to various parts of Russia is serviced during and after the guarantee period at the Service Center at EFSE (Chernogolovka).

The special design office of EFSE has designed and manufactured a batch of Evromekhanika constructs of various sizes in accordance with the IEC 297 standard and a series of hardware devices based on the open dataway–modular standards VME and PCI, including a wide range of communication-with-object modules and programmed controllers with built-in commercial processors.

In order to solve the problems that challenge the creators of automatic control systems for technological processes of the upper and lower levels as applied to specific industrial units, the hardware – software complex TURBOKOM-4011 developed in cooperation with the TEKHNOKOM-micro Company has been employed. This complex is intended for designing multilevel distributed systems used in the automation of technological processes. EFSE has received a licence from the State Atomic Inspection Committee to design and produce automation equipment for atomic energy stations.

During recent years, in order to retain the high technological standards in manufacturing analytical instruments and producing high vacuum and also taking into account the growing market for instruments involved in such activities, EFSE has developed, in cooperation with the Institute for Analytical Instrument Making of the Russian Academy of Sciences, and assembles the chromato-mass-spectrometer MSD-650. The latter is intended for qualitative and quantitative analysis of toxic components of mixtures of organic compounds and their identification. This is the first Russian-made top-grade instrument that allows the identification of supertoxicants, including dioxins. The instrument has been certified by the State Standards Committee of the Russian Federation in the State Registry for Measuring Devices (Certificate No. 1297). The MSD-650 spectrometer is used to develop new instruments, in particular, mass spectrometers with a glow discharge for the analysis of inorganic substances.

The implementation of the program of developing high technologies, the production and delivery of knowledge-intensive products to various parts of Russia and abroad have made it possible to transform the plant into a profitable and competitive enterprise.

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Femtosecond photoelectronics — past, present, and future

M Ya Shchelev¶

1. Introduction

Among the diagnostic methods and techniques used in experimental physics to study fast processes (FP), high-speed electron-optical photography is distinguished by its record-high speed (the theoretical limit of the time resolution is 10 fs = 10^{-14} s), the large volume of spatial data recorded simultaneously (up to $10^6 - 10^8$ resolvable elements), an extremely high sensitivity (each electron emitted by the input

¶ The author is also known by the name M Ya Schelev. The name used here is a transliteration under the BSI/ANSI scheme adopted by this journal.

photocathode is detected), a broad spectral recording range (from soft X-rays to the near infrared radiation), and the possibility of rapid (fractions of a second) input of recorded FP images into a computer for storage, processing, visualization, and data analysis. The key device of any image-converter camera (ICC) that fixes in time a sequence of FP image phases is the time-analyzing image-converter tube (ICT). This device performs a linear (in intensity) conversion of an optical FP image in the photocathode film (100 – 300-Å thick) into its photoelectronic analog, focuses this photoelectronic image onto the output screen [luminophor layer, vidicon target, or charge-coupled device (CCD sensor)] and 'disperses' in time either the entire photoelectronic image or a part of it limited, say, by a narrow slit into some pattern over the output screen. Here, the phase velocity of the image movement over the screen may exceed the speed of light severalfold, which is due to the almost lag-free deflection of the electron beam controlled by a rapidly varying electric field. As a result, each spatial element of the photoelectronic image, δ, time-dispersed along the direction of sweep corresponds to a definite time interval, with the shortest recorded time interval being $\Delta t = \delta / V$, where V is the linear sweep speed. For commonly used ICCs operating in the linear sweep mode (streak cameras), the minimum size of the resolved spatial element (in the static mode, i.e. without sweep) may approach $(1-2) \times 10^{-3}$ cm, and the phase sweep velocity may exceed 10^{11} cm s^{-1}. This means that the accuracy of the time reading may reach 10^{-14} s (at least theoretically). Naturally, one must account for the quantum-mechanical nature of the interaction of the electrons and the deflecting field, which may lead to the shot effect in the beam deflection and, as a result, to disordered fluctuations of the sweep speed. Estimates have shown that these fluctuations do not exceed 10^{-15} s.

When at the beginning of the 1930s ICTs were invented [1], nobody even thought that they could be used in high-speed photography. It was assumed that night-vision devices using invisible IR radiation would be constructed around these image tubes, thus permitting one to examine the objects of interest. The first ICTs had a photocathode and a luminescent screen positioned parallel to the cathode, with an accelerating voltage applied between the cathode and the screen. In a uniform electric field the photoelectrons fly along parabolas, thus producing a blurred image of the object. At the beginning of the 1940s, Lev Artsimovich in the Soviet Union [2] and scientists in Germany and the United States [3 – 6] increased the spatial resolution of ICTs to several dozen pairs of lines per millimeter by focusing the image in the electrooptical converter using electrostatic and magnetic lenses.

Towards the end of the 1940s and the beginning of the 1950s, the first attempts were made to introduce pulsed night-vision ICTs. These were later exploited to study the temporal characteristics of pulsed sources of light. Vanyukov and coworkers [7] used German night-vision ICTs to realize exposures with a duration of $10^{-6} - 10^{-8}$ s. In Great Britain, J Courtney-Pratt applied an alternating magnetic field to similar electrooptical converters and attained a time resolution of 10^{-9} s in the photoelectron-image sweep [8].

However, the crucial step in image-converter tube making was taken by M Butslov, who in 1949, acting on a proposal made by E Zavoĭskiĭ, placed four pairs of capacitor type plates (similar to those used in oscilloscopes) for sweeping and cutting off the image via rapidly varying electric fields into an ICT with an electrostatic focusing system (to the beam region of a minimum cross section) [9]. In 1952, Butslov built the world's first multistage ICT with magnetic image focusing. In it he used the principle of optical contact of the luminescent screen of each previous stage and the photocathode of the next stage through a micrometer-thick mica film [10]. Later on (see Ref. [11]), an ICT with electrostatic focusing and a five-stage ICT with magnetic focusing were combined and placed inside a vacuumed envelope, which led to the fabrication of unique time-analyzing ICTs capable of recording every photoelectron that left the entrance photocathode (Fig. 1). With these tubes, pico-femtosecond time resolution was attained [12]. It is notable that in other countries multistage pulsed electrooptical converters were never built.

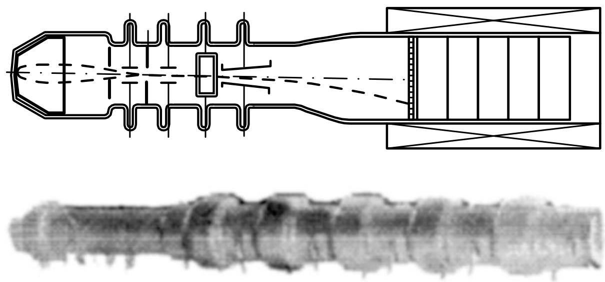
a
b

Figure 1. First Soviet picosecond UMI-95 ICT (UMI stands for 'multistage pulsed amplifier' in Russian): (a) block diagram, and (b) general view.

Thus, almost 50 years ago the Soviet scientific school pioneered a new area of technical physics and scientific instrument making, femtosecond photoelectronics. Today this interdisciplinary line of inquiry is focused on the development of diagnostic methods and facilities for direct detection of one- and two-dimensional FP patterns with a time resolution amounting to several dozen femtoseconds in the spectral range from soft X-rays to the near infrared radiation with a sensitivity sufficient for detecting several dozen quanta in a spatially resolved element and a dynamic recording range spanning more than four orders of magnitude. This line is extended through research in the physics of photoemission, photocathodes with negative electron affinity (NEA) and classical-type photocathodes, electron optics and computer simulations, the physics of femtosecond lasers, vacuum technologies used in the production of electronic devices, mass spectrometry of gases and image-converter instrument making, digital input, processing and visualization of the time-dispersed photoelectronic images. The equipment fabricated on the basis of these studies has already made possible unique experiments in laser physics, nonlinear and fiber optics, the physics of laser-induced plasma and laser-induced fusion, laser kinetic spectroscopy, and femtosecond diffractometry. Further improvements of the methods and facilities for electron-optical diagnostics will produce striking results in the near future in developing femtosecond information systems, in experiments involving new materials and chemical technologies, and in femtochemistry.

2. Time-resolution limit of ICTs

From 1953 – 1955, E Zavoĭskiĭ and S Fanchenko used a multistage pulsed ICT to do experiments on the detection of light generated by high-frequency ($10^{10} - 10^{11}$ Hz) spark discharges in nitrogen under high pressures. A phase-shifted sinusoidal voltage at 300 MHz was applied to two mutually perpendicular plates of a time-analyzing ICT, which produced a continuous elliptical time scan on the screen of the tube. For a maximum sweep speed of 2×10^9 cm s^{-1}, the corresponding time-resolution component amounted to roughly 5 ps. Figure 2 depicts a photograph of the time scan of the oscillating discharge channel of an ultraminiature spark. The overall duration of the discharge was 200 – 400 ps, and short light pulses 10 – 20-ps long were observed inside the discharge channel.

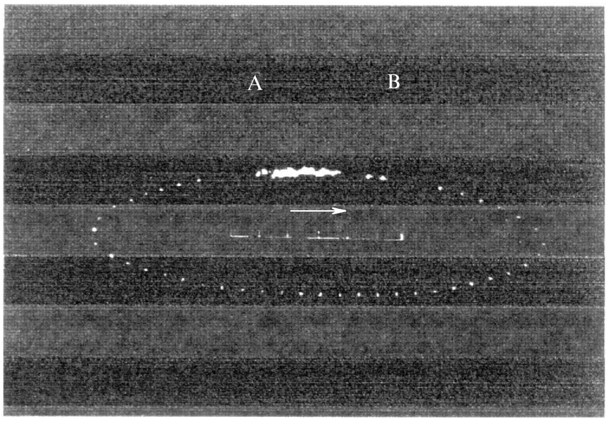

Figure 2. Time scan of the oscillating discharge channel of a miniature spark on the screen of an ICT. The light dots indicate the elliptical path of the time-base, with the time scale being 100 ps per division.

Being the first to attain a time resolution so high in a direct experiment, Zavoĭskiĭ and Fanchenko posed themselves a more general question: What are the fundamental physical limitations on the ICT time resolution? They formulated the principles following which one could ensure a 10-fs time resolution for ultrafast electron-optical chronography [13]. The essence of these principles is as follows:

(a) The greatest attainable time resolution of ICTs is limited by the spread in the transit time of the photoelectrons travelling from the photocathode to the screen, is directly proportional to the spread in the initial velocities of the photoelectrons (ΔV_{0z}), and is inversely proportional to the strength of the accelerating electric field at the photocathode (E_0). For classical semitransparent photocathodes (silver – oxygen – cesium, Ag – Cs – O, and multialkaline, Na – K – Cs – Sb, photocathodes) operating via the photoemissive effect and sensitive to ultraviolet, visible, and near infrared light, the researchers arrive at an estimate relationship that links the time resolution, determined by the chromatic aberrations of the photocathode, to the strength E_0 of the electric field at the photocathode, generated by the focusing lens: $\tau_{\text{chr}} = \alpha \times 10^{-11}/E_0$. Here α is a coefficient that depends on the type of photocathode and the wavelength of the input radiation and has a value between one and five. The field strength E_0 was expressed in units of electrostatic potential (1 esu = 30 V mm^{-1}). According to this relationship, to attain a time resolution of approximately 10 fs, the field strength at the photocathode must be in the 30 – 150-kV mm^{-1} range. Notice that the field strength in multistage pulsed PIM-UMI type ICTs (PIM stands for 'multiframe pulsed converter' in Russian) amounts to only 60 V mm^{-1};

(b) The time resolution of ICTs depends on the spread in the transit time of photoelectrons within the photocathode layer, the spreading of electron wave packets as they move from photocathode to screen, and the pulling of the light signals with the entrance optics. With allowance for only these factors the time resolution of image-converter photography can be made equal to 10 fs;

(c) In photographing images with pico-femtosecond time resolution it is essential that the brightness of the images after their sweeping in the time-analyzing stage be enhanced substantially (by a factor of $10^4 - 10^6$). This is needed for reliable recording of time-scanned images, whose intensity is usually insufficient for direct recording by the image receiver;

(d) The intensity of the electron beam in the time-analyzing cascade cannot be raised above a certain limit, which is determined by Coulomb repulsive forces. These forces lead to a 'swelling' of the photoelectron wave packet and, in the final analysis, to a drop in the time resolution of ICTs and to violation of the linearity of the image-tube transfer function. While making estimates, the researchers derived a relationship linking τ_C to the number of electrons, n, per image element: $\tau_C \sim 10^{-14} n$. This means that to retain the time resolution at a level of 10 fs, the number of electrons per image element must not be more than one. In this case the recorded image will consist of separate dots, and the reproduction of half-tone image gradations will require image accumulation, and

(e) The sweep of electron-beam images of fast processes must proceed at high phase velocities. For instance, for streak velocities that exceed the speed of light by a factor of 3 to 10, the greatest attainable time resolution may be in principle as low as 10 fs.

The technical realization of many of the above statements has taken many years, but the potential of increasing the time resolution of ICTs by three orders of magnitude has constantly drawn the attention of researchers. However, femtosecond ICTs have become claimed only in the last few years, when lasers generating light pulses of femtosecond duration became operational.

Even before the first lasers appeared, time-analyzing ICTs have started to be intensively employed in nuclear physics to study spark counters of ionizing particles [14], to photograph Cherenkov radiation produced by an individual relativistic charged particle [15], and to synchronize in time the moment of arrival of colliding beams of relativistic electrons in experiments involving synchrotron radiation [16], and in controlled fusion experiments to determine the density, the partial composition and the electron temperature of the plasma from the intensity of the spectral lines [17]. The advances of using time-analyzing ICTs in physical experiments were also a powerful stimulus to improving the ICTs proper, while the resulting demand in electron-optical diagnostic facility led to the need for manufacturing such devices in small batches. For instance, a batch of image converter cameras of the subnanosecond range for photographic recording of fast processes in the framing and streak modes was developed at the Institute of Automatics and Electrometry of the Siberian Branch of the Russian Academy of Sciences under the aegis of Yu E Nesterikhin [18]. The cameras were built around original ICTs designed at the Institute, namely, two-electrode tubes (of ZIM type), which ensured a frame exposure of 0.5 ns, and three-electrode tubes (of ZIS type) with deflecting plates and a grid gate. On the basis of the extensive experience of the Kurchatov Institute of

Atomic Energy [19] and with active participation of M I Pergament [20], a large batch of LV-01/LV-04 type 'time magnifiers' were manufactured at the Sumy (Ukraine) Electron Microscope Plant [21]. With a maximum streak speed of 10^8 cm s^{-1}, these cameras ensured subnanosecond time resolution and a minimum frame exposure of 50 ns. The experimental elaboration of cameras based on PIM-UMI image tubes was put into effect by Nesterikhin and Komel'kov of the Kurchatov Institute of Atomic Energy [22], Yu Drozhbin of the Institute of Earth Physics, RAS [23], L Pyatnitskiĭ and coworkers of the All-Union Electrotechnical Institute [24], V Muratov and E Nilov of the State Optical Institute (St. Petersburg) [25], and many other researchers. A batch of LVE brand 'time magnifiers' and FER brand image-converter cameras were manufactured at the All-Union Scientific Research Institute of Optical Physics Measurements (VNIIOFI in Russian) under the aegis of B M Stepanov (see Ref. [26]).

All in all, by the beginning of the 1960s, extensive experience in the development and successful application of image-converter instrumentation in physical experiments had been accumulated in the USSR.

3. Electron-optical instrumentation at the FIAN and the laser 'boom' of the 1960s

The P N Lebedev Physics Institute (FIAN in Russian) of the USSR Academy of Sciences estimated the potential of ultrafast electron-optical diagnostics at its true worth when in 1962 – 1970 the Spectroscopy Laboratory headed by S L Mandel'shtam developed image-converter cameras on the base of the then existing PIM-UMI type time-analyzing ICTs. In the process of designing these cameras, new original circuit-engineering solutions were found and the best elements of pulsed nanosecond technique were employed, such as spark gas-discharge peakers [27], microwave triodes operating in the pulse-grid modulation regime, broadband cable inverters and transformers, and high-Q-factor secondary-emission vacuum tubes [28]. The equipment built at FIAN (Fig. 3) spanned a recording range from 5×10^{-10} to 10^{-2} s in the linear-sweep regime, while in the single-frame regime it spanned a recording range from 5×10^{-9} to 10^{-2} s. The equipment had a short triggering time approaching 20 ns (± 0.1 ns), a high sensitivity sufficient for detecting a single electron that has left the input photocathode, and a subnanosecond time resolution [29, 30]. At the FIAN workshop, a batch of pilot electron-optical hardware for equipping the experiments conducted at the various FIAN laboratories was manufactured. More than two hundred high-voltage regulated power supply units for ICTs were designed at FIAN and manufactured at the Special Design Office of the Institute of Terrestrial Magnetism, Ionosphere, and Propagation of Radio Waves of the USSR Academy of Sciences [31].

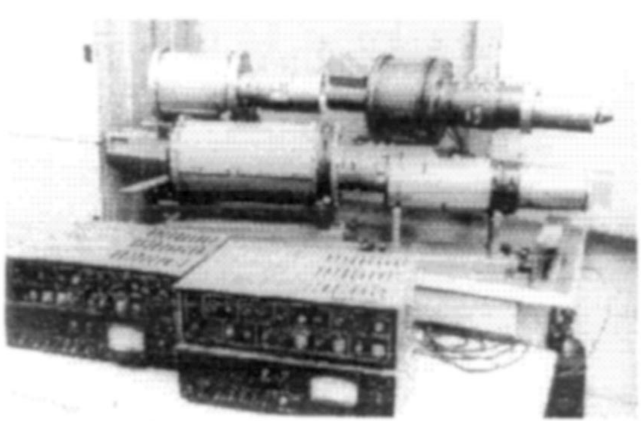

Figure 3. Electron-optical equipment developed at the P N Lebedev Physics Institute (FIAN).

The new equipment was first used in M D Galanin's laboratory at FIAN by a group of researchers headed by A M Leontovich to study the lasing of a free-running ruby laser. The methods and measuring techniques used earlier (oscilloscopes and optomechanical cameras) either did not produce a spatial pattern or had an insufficient time resolution. V V Korobkin was the first to use an image-converter camera in studies of the discrimination of axial modes in a ruby laser [32]. The effect was astounding: two Fabry – Perot interferometers with different dispersion regions simultaneously produced pictures (on the screen of an ICT with 100-ns exposures) of the spectral composition of the radiation generated in any of the microsecond spikes of the laser radiation with an overall length of several milliseconds. Moreover, experiments studying the dynamics of the laser field, wavefront, spectrum, and coherence in a giant pulse generated by a ruby laser proved possible only thanks to the subnanosecond (0.5 ns) time resolution and high spatial resolution (no less than 20 line pairs per millimeter) of the equipment developed at FIAN (Fig. 4) [33].

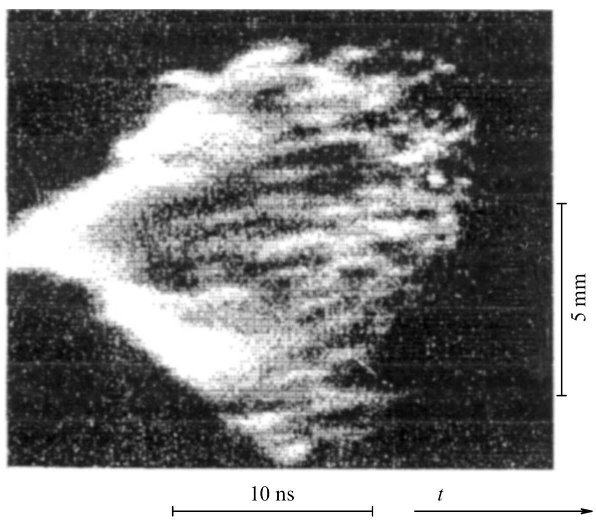

Figure 4. Dynamics of the laser field (near zone) generated by a ruby laser operating in the Q-switched mode.

These first experiments attracted the attention of researchers and confirmed the high information capacity of electron-optical high-speed diagnostics. On the suggestion of A M Prokhorov and P P Pashinin, an ICT was used at the Oscillation Laboratory to record a spark in air, produced by focusing laser radiation [34]. What was recorded was the motion of the ionization front, produced by sequential laser-spark-induced breakdowns (Fig. 5). I L Fabelinskiĭ conducted an experiment in which an ICT was invoked to study stimulated Brillouin scattering (SBS) in gaseous nitrogen under a pressure of 150 atm [35]. G A Askar'yan and V N Lugovoĭ initiated the exploration of the kinetics of self-focusing in nonlinear liquids. These experiments corroborated the existence of a multifocus structure and made it

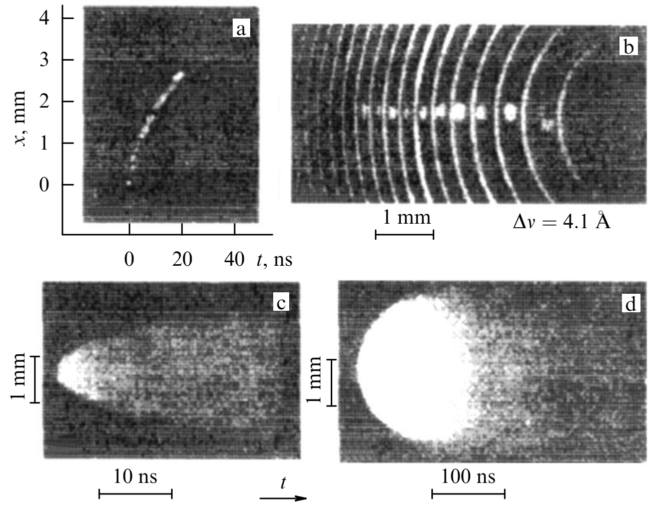

Figure 5. Track of a laser spark moving towards a lens. The spark was produced by focusing the laser radiation from a Q-switched ruby laser in air: (a) the picture in reflected light; (b) Doppler shift of the reflected laser beam travelling along the spark channel, and (c), (d) radial expansion of the spark plasma.

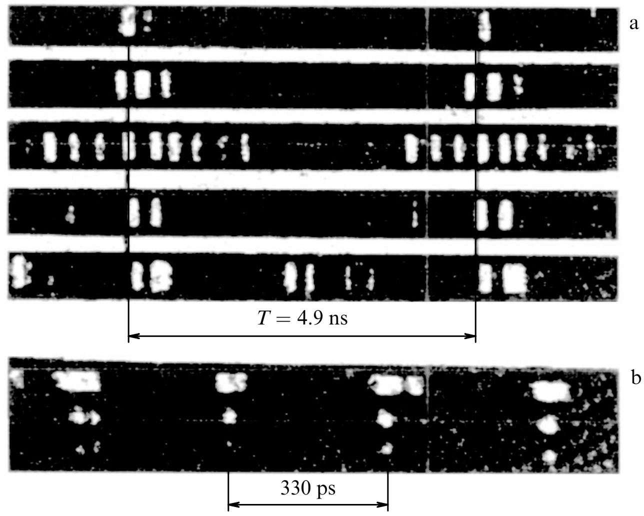

Figure 6. Time structure in the light emitted by a Nd-glass laser operating in the passive mode-locked regime: (a) pictures taken in separate axial intervals ($T = 4.9$ ns) in periodically recurring light flashes, and (b) the fine time structure within a separate axial interval.

possible to interpret the self-focusing filaments as the result of the motion of focal points (this phenomenon was registered as an invention) [36].

In 1968, a group of researchers headed by V I Malyshev (FIAN) developed the first Nd-glass laser with passive mode locking achieved by using a bleachable dye. This research (see Refs [37, 38]), done practically simultaneously with research done in the United States, laid the ground for studying a new type of laser, the passive mode-locked lasers [39], in which a periodic train of ultrashort light pulses appeared when a nonlinear absorber (a solution of an inorganic dye) was placed inside the cavity of a ruby or Nd-glass laser [40]. The introduction of the absorber made the laser operative in the Q-switched and self-mode-locked regimes simultaneously.

By that time the image-converter equipment at FIAN had undergone substantial modification, and its time resolution determined by the sweep speed was brought up to roughly 5 ps. This had an immediate effect in applications. A fine time structure was detected in the light emitted by a Nd-glass laser; the structure was related to the emergence in the axial interval of additional lasing spikes, including those that appeared because of discrimination of axial modes by elements of the laser cavity (Fig. 6) [41]. The discrepancy in the experimental data that existed at that time was that the oscillograms with the greatest attainable time resolution 300 ps exhibited a train of regular, single pulses during the axial interval, while the two-photon luminescence pattern indicated that the lasing train contained very short pulses, $\sim 1.5-3$ ps, and longer pulses, $\sim 15-30$ ps. The employment of ICTs made it possible to observe the real structure of the laser radiation and to decide in what way to improve solid-state lasers operating in the passive mode-locked regime. At roughly the same time, Kryukov and Letokhov [42] proposed and substantiated a mechanism that provided the first explanation concerning the formation nature of ultrashort radiation pulses from fluctuation surges (what became known as the fluctuation model).

A group of researchers at the Quantum Radiophysics Laboratory headed by N G Basov and O N Krokhin used a high-power Nd-glass laser to study the heating of plasma produced by ultrashort laser pulses. A laser pulse 10-ns long consisted of several 10-ps spikes separated by intervals of 1–2 ns and had an overall energy of 0.1 J. The experiments were conducted with a focal spot diameter on a flat target of roughly 0.2 mm. A camera with an ICT took pictures of the plasma expansion in the blue-green spectral region, and the speed of propagation of the glow in the direction opposite to that of the laser beam was found to amount to $(0.8-1.5)\times 10^7$ cm s^{-1} [43]. It was also found that up to 30% of the incident energy is reflected by the target.

The image-tube equipment developed at FIAN allowed measurement of the broadening of ultrashort light pulses after they had passed through an optical fiber as a function of the aperture of the light beams used in the measurements [44]. The input pulses 10–15-ps long broadened to 30–40 ps after passing through a fiber segment 260-mm long.

As the use of electron-optical apparatus in laser studies became more popular, the problem emerged of establishing reliable ways of certifying the operating parameters and, in particular, of measuring the time resolution [45]. By employing laser technology it became possible to create a number of techniques enabling ICTs to become an instrument of quantitative analysis. The successful experiment involving the picosecond Nd-glass laser posed the question of accuracy with which an ICT measures the temporal profile of laser pulses. The ICT on hand did not record single shots with a halfwidth shorter than 10–20 ps. Sine-modulated radiation with a known period and modulation depth was then fed to the ICT input. The halfwidth of the time-dependent instrument function was calculated by using the equation for convolution of the input signal and the instrument function under the assumption that the envelope of the latter function has a Gaussian profile. The recorded minimum beat period amounted to 30 ps for a percentage modulation no less than 20%, which amounts to the minimum value of the halfwidth of the instrument function being no longer than 15 ps for input radiation with $\lambda = 1600$ nm and no longer than 30 ps for input radiation with $\lambda = 530$ nm. Here, the streak speed amounted to 5×10^9 cm s^{-1} (i.e. the sweep resolution $\leqslant 5$ ps did not limit the accuracy of measurements), and an enhancement in brightness close to that needed for detecting single photoelectrons emitted by the input photocathode was maintained. The electric field strength at the photocathode changed from 60 to 120 V mm^{-1} due to the increase of the accelerating voltage fed to the time-analyzing ICT by a factor of two. The results of these experiments led to the conclusion that the PIM-UMI type ICTs in our possession provide the greatest time resolution possible for such image tubes, and that this time resolution is limited primarily by chromatic aberrations of the electron lens. Further narrowing of the halfwidth of the time-dependent instrument function is possible only by substantially increasing the strength of the accelerating field at the photocathode and also by decreasing the energy spread of the photoelectrons by monochromatizing the electron beam or by using input radiation that is close in frequency to the long-wavelength cutoff of the photocathode.

Thus, in the 1960s the main principles of ultrafast image-converter photography were successfully corroborated. The 10-ps limit in time resolution was achieved for the then existing ICTs, while electron-optical methods of research became widespread in everyday laser studies and made it possible to get experimental results that could not have been accomplished with any other instrumental methods and aids.

4. New-generation picosecond ICTs and image-converter cameras

The fabrication of picosecond lasers aroused new interest in studies in the field of laser-induced plasmas, nonlinear and fiber optics, photobiology, and spectroscopy. This in turn had a stimulating effect on research aimed at overcoming the 10-ps limit of the then existing ICTs. Since 1971 at FIAN and 1983 at the Institute of General Physics of the Russian Academy of Sciences (IOFAN in Russian), Academician A M Prokhorov has headed a series of studies in applying time-analyzing ICTs to laser physics and optics, in designing new diagnostic facilities, and in establishing international cooperation in electron-optical instrument making. He actively supported the opening in 1965 of the All-Union Scientific Research Institute of Optical Physics Measurements (VNIIOFI), initiated close ties with the institute and organized there joint research projects in the field of novel time-analyzing ICTs. Among the scientists who headed this work at VNIIOFI in different periods of time were M M Butslov, B M Stepanov, and G I Bryukhnevich.

The modernization of PIM-UMI tubes amounted to designing electrostatic lenses that use higher electric fields at the photocathode and introducing high-frequency electron-image sweep systems into ICTs. For instance, using the results of the research by P A Tarasov, R V Chikin and others, VNIIOFI developed, at the request of the Kurchatov Institute of Atomic Energy, a new multistage Pikokhron-type time-analyzing ICT [46, 47]. In this device the electric field strength at the photocathode was increased, due to a change introduced in the configuration of the focusing lens, by a factor of ten and amounted to 600 V mm^{-1}. The capacitor-type deflecting plates were replaced by two mutually perpendicular open cavities tuned to 3 GHz (in later experiments, the cavities were tuned to 10 GHz). As a result, the maximum circular sweep speed attained with this device was $(5-6)\times10^{10}$ cm s^{-1}, which limited the time resolution to 0.2 – 0.5 ps. By varying the configuration of the deflecting fields one could change the shape of sweep to circular, elliptical, trochoidal, or panoramic, which results in much longer recording times with the time resolution remaining unchanged. Using the Pikokhron ICT, Fanchenko and Kryukov and coworkers observed separate spikes (1.7 – 5)-ps long at the beginning of the pulse train generated by a self-mode-locked Nd-glass laser [48, 49].

In 1970, Alcock, Richardson, and the present author conducted joint experiments at National Research Council (Canada) that irrevocably corroborated the need to increase the electric field intensity at the photocathode using accelerating meshes. In these experiments the researchers availed themselves of a standard tube (RCA C73435) with a grid at the photocathode. Initially the grid was designed for cutting off or opening the image in framing photography. In the case being discussed the grid was used to increase the electric field strength at the photocathode up to 360 V mm^{-1} (i.e. the field intensity was increased by a factor of six in comparison to the value used in PIM-UMI tubes). The maximum sweep speed was also increased by a factor of three and reached 1.6×10^{10} cm s^{-1}. The time-analyzing tube was joined through high-aperture lenses with a four-stage image intensifier (EMI 9694) with a gain of 10^6, which guaranteed the detection of single photoelectrons emitted by the input photocathode. Under these conditions the minimum length of the light pulses generated by a self-mode-locked Nd-glass laser and recorded in the experiments amounted to 5 ps at $\lambda = 1.06$ μm. For this series of experiments an original equipment was built to control a new experimental picosecond camera [50]. The control equipment was based on a laser-triggered high-voltage nitrogen-filled (20 atm) spark gap operated at 15 kV as well as cryotrons, avalanche transistors, and microwave triodes.

At the beginning of the 1970s, a new generation of image tubes was developed at VNIIOFI at the request of FIAN. A tube of this type had a finely structured accelerating grid (the mesh size was 30×30 μm) placed at a distance of 1 mm from the photocathode. This grid ensured an increase in the field intensity by a factor of almost 100 (3 kV mm^{-1}). To reduce the image defocusing when large pulse currents (up to several amperes per square centimeter) flow through the photocathode, its surface resistance was reduced to 5 – 10 Ω cm^{-2}. Silver – oxygen – cesium photocathodes (Ag – Cs – O) with a long-wavelength cutoff of 1.3 – 1.5 μm were fabricated in a separate vacuumed volume, and after a thorough check were placed inside the ICT by a vacuum manipulator. The deflecting systems of the new ICTs were made in the form of broadband (up to 3 GHz) strip lines matched at their ends to coaxial lead-ins. The time-analyzing image-converter tube was connected via thin sheets of mica to a three-stage image intensifier with magnetic focusing. By combining such devices with ultra-wide-aperture lenses and supersensitive emulsions it became possible to detect single photoelectrons.

To perform dynamic tests of the new types of UMI tubes with an accelerating grid in proximity to the photocathode a test bench was constructed on the base of a two-frequency Nd-glass laser that generated only two spectral components [51]. The earlier proposed method of mode beats proved to be a reliable tool for improving the tubes since single picosecond shots generated by a self-mode-locked Nd-glass laser were unstable in duration. Moreover, even with a Nd-glass laser with a fastly relaxing dye the minimum duration of single shots amounted to 1 – 2 ps [52].

A subpicosecond time resolution amounting to 0.7 ps was attained at FIAN for the first time in 1976 [53]. The research

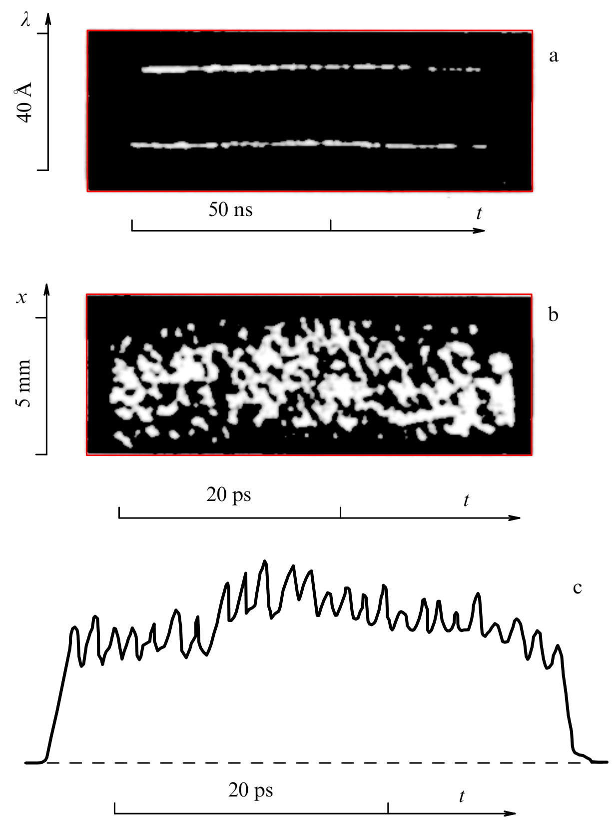

Figure 7. (a) Sweeps of two spectral components in the light emitted by a *Q*-switched Nd-glass laser, (b) the picture of 1.4-ps mode beats taken from the screen of the ICT, and (c) the corresponding microdensitogram.

group used an UMI-93M tube which recorded sine-modulated laser radiation with a period of 1.4 ps and a percentage modulation higher than 10% at $\lambda = 1060$ nm (Fig. 7). The sweep speed reached in this case 5.5×10^{10} cm s^{-1}, and the electric field strength at the photocathode was greater than 3 kV mm^{-1}. The main element of the camera was a laser-triggered spark gap, which formed squared pulses with subnanosecond fronts and an amplitude of up to 20 kV. A pulsed ICT provided reliable recording of each electron emitted by the input photocathode, which was an oxygen – silver – cesium photocathode with a surface resistance no higher than 10 Ω cm^{-2} and a total sensitivity of 20 μA lm^{-1}.

To study the interaction between high-power picosecond pulses of radiation and a target matter and to develop methods of picosecond X-ray diagnostics for laser-induced controlled fusion, VNIIOFI developed and fabricated (at the request of FIAN) time-analyzing ICTs sensitive to radiation in the soft X-ray region (1 – 10 Å). The entrance window in such ICTs was a mica film 3-μm thick, and the new two-component photocathode (Au + SbCs) invented at FIAN was sensitive to radiation in the visible and X-ray ranges. The sensitivity of the two-component photocathode to X-rays is much higher than, say, the sensitivity of a gold photocathode due to the secondary emission of photoelectrons in the SbCs layer. Since the duration of secondary emission is about 10^{-16} s, the time resolution of two-component photocathodes remains very high. Such ICTs were used as a component in a picosecond X-ray camera developed at FIAN to study the X-ray emission produced by the plasma that was created in the process of irradiating a massive titanium target with 10-ps focused laser pulses with an energy of 1.3 J per pulse. The minimum recorded length of the pulses achieved with the X-ray tube UMI-93SR in the 0.1 – 1-nm spectral range amounted to 12 ps at a sweep speed of 3×10^9 cm s^{-1} and with a field strength at the photocathode higher than 3 kV mm^{-1} [54].

Note that the X-ray (100 eV – 30 keV) image-converter cameras built somewhat later by D T Attwood, G L Stradling and others [55] at the Lawrence Livermore Laboratory, in Livermore, California, also ensured a maximum time resolution of about 15 ps.

The picosecond X-ray cameras developed at FIAN were used in experiments headed by A A Mak of the State Optical Institute (St. Petersburg). Solid targets of $(CD_2)_n$ with a diameter $\geqslant 100$ μm were irradiated with picosecond laser pulses from a high-power Nd-glass laser. A packet of several pulses with an overall length smaller than 800 ps was emitted by the laser. The energy per pulse at the target surface amounted to 30 – 50 J with an energy contrast better than 10^4. The X-ray emission produced by the plasma followed the temporal profile of the heating pulses, with the X-ray pulses at the end of the packet being shorter than those at the beginning [56].

Further improvement of time-analyzing ICTs took the form of replacing the bulky and complicated-in-service multistage image intensifier with a microchannel-plate (MCP) image intensifier with a gain of $10^4 – 10^5$. A microchannel plate with a thickness of roughly 1 mm involved up to $10^6 – 10^8$ channels having a diameter of several micrometers each and was placed in a longitudinal electric field in a vacuum chamber. The gain of this device was controlled by varying the voltage applied to the plate (0.5 – 1 kV). The electrons were multiplicated in the channels due to collisions with the microchannel walls, which had a high secondary emission ratio. Experiments were carried out in which MCPs were placed directly inside a time-analyzing ICT in front of the tube's screen. This led to the fabrication of a compact device named PIM-MK-1 [57], around which the experimental camera was built. However, later on the time-analyzing ICTs and MCP image intensifiers underwent improvements in separate vacuum envelopes, and only after this stage they were combined by optical contacts through optical-fiber disks. The most successful design of ICT (which employed what is known as a dumping accelerating grid) protected by dozens of foreign patents [58] was embodied in tubes known by the PV brand (PV stands for time-analyzing converter in Russian). These tubes had a constant electron-optical magnification factor within a broad range of grid voltages (0.1 – 6 kV). The spectral sensitivity of their oxygen – silver – cesium photocathodes was no less than 500 μA W^{-1} at $\lambda = 1060$ nm and of order 0.5 μA W^{-1} at $\lambda = 1550$ nm. Tubes of this brand were produced in the hundreds, and they are still being manufactured.

On the base of PV tubes and microchannel image intensifiers, VNIIOFI developed the Agate commercial camera [59], which successfully replaced the FER cameras built around PIM-UMI tubes. At the request of FIAN, the Physics Instrument Making Special Design Office also produced a large pilot batch of compact ICC-2M-type picosecond (with a maximum time resolution of 1.5 ps) cameras (Fig. 8) [60, 61]. Some of the cameras of this batch were supplied to the State Optical Institute in St. Petersburg, while others remained in FIAN's Oscillation Laboratory. These cameras used pulsed control circuits developed by a group of researchers (including the author of this report) in

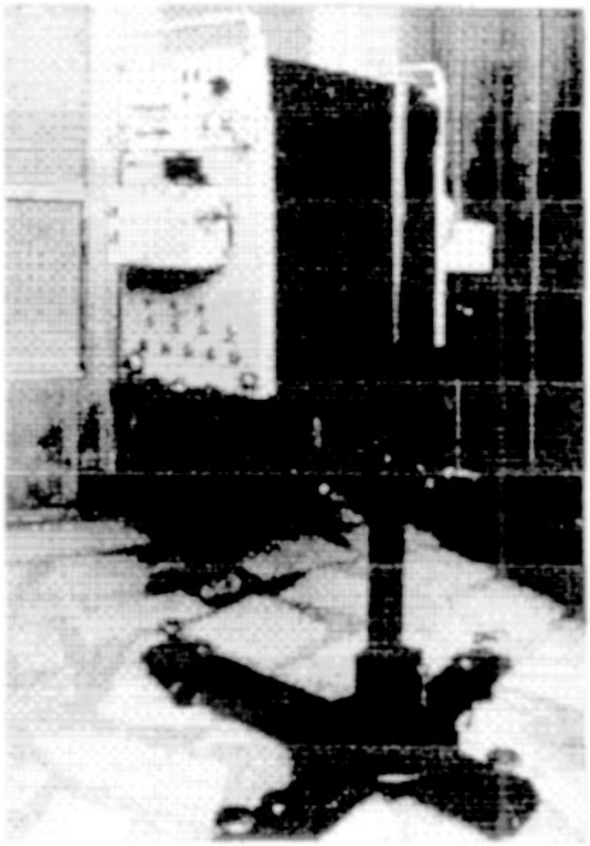

Figure 8. Small-batch camera ICC-2M.

collaboration with J Thebault, J A Miehe and others during traineeship at the French Commissariate à l'énergie atomique in Saclay [62]. These control circuits ensured direct measurements by streak cameras of the frequency departure in a single high-power picosecond shot [63] and observation of the temporal evolution of the spectral components in the Raman scattering excited in CCl_4 by strong picosecond pulses [64]. These experiments were initiated by J P Gex.

ICC-2M-type streak cameras made it possible for the first time to directly measure the duration of picosecond light pulses that emerge as a result of self-locking of many (up to 15) Stokes components of stimulated Brillouin scattering (SBS) [65]. The conversion of the exciting radiation into SBS reached 80–90%, and an initial pulse 30-ns long was scattered into a regular train of spikes with a length of roughly 30 ps each.

The use in pulsed fluorimeters of a specially designed (at FIAN) ICC-3 camera equipped with two MCP image intensifiers ensured direct recording of the kinetics of the fluorescence decay in the reaction centers of photosynthesizing organisms. The experiments were carried out by a group of researchers headed by L B Rubin at the Biological Department of Moscow State University (see Ref. [66]). In experiments that involved the reaction centers of purple bacteria, the temperature dependence of the fluorescence time was measured in the 2–200-ps range, and it was found that electrons are transferred from bacteriochlorophyll to bacteriopheophytin by the tunneling mechanism.

To analyze the vibration spectra in reactions with a sudden temperature jump initiated by the radiation of a high-power picosecond laser in solutions of biological macromolecules, a group of researchers including the present author joined forces with a group of French scientists and used picosecond streak cameras to build a multichannel picosecond Raman spectroscope (see Ref. [67]).

The active introduction of picosecond electron-optical diagnostics into laser studies posed the problem of building systems that would be able to rapidly process and visualize images of fast processes recorded by ICTs. This led to the building of several variants of picosecond electron-optical information systems, each of which incorporated a laser source of light for dynamic calibration of the ICT, a readout device based on supersensitive vidicons (later on CCD sensors were invoked), and a personal computer for storing, processing, and visualizing the images recorded on the screen of the streak camera. One of the first information recording systems is shown in Fig. 9 [68]. It is based on an ICC-3 camera and a low-light level TV-camera. Later more advanced cameras ICC-4 were used in related information systems. In such cameras the circuits that controlled the electron image were built around subnanosecond semiconductor sharpeners developed at the Leningrad Physico-Technical Institute by I V Grekhov and others [69].

At the end of the 1970s, the technique for digital image processing received a large development effort. This technique was used to correct, restore, and estimate the parameters of fast processes from the images recorded on ICCs [70]. This work was done in close cooperation with A G Sveshnikov's chair on the Physics Faculty of Moscow State University. The possibility of improving the operating characteristics of the equipment without drastic modifications was demonstrated, which was done by processing the images *a posteriori* with the help of data on the instrument function and stochastic data on the event being studied.

An outstanding event that summed up the results obtained over a period of almost 30 years in image-converter scientific instrument making in the USSR and abroad was the

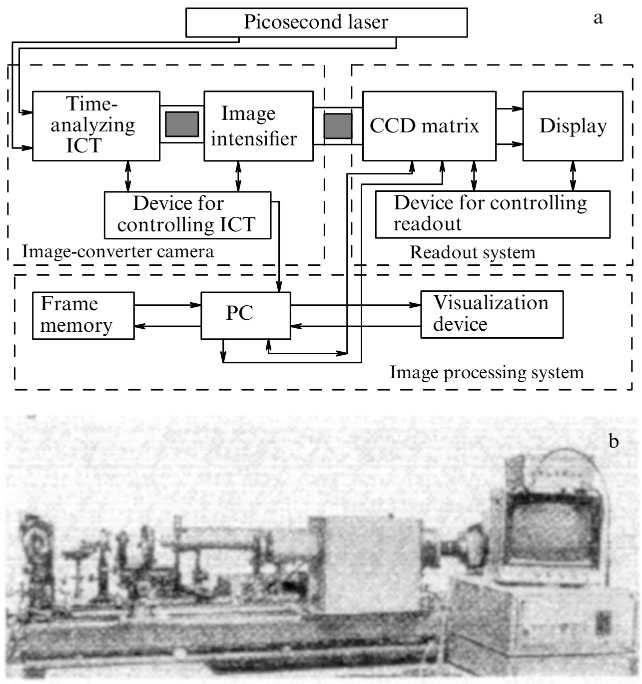

Figure 9. Picosecond electron-optical information system based on an ICC-3 camera and a supersensitive vidicon: (a) block diagram, and (b) general view.

14th International Congress on High-Speed Photography and Photonics held in Moscow in October 1980. The speech of welcome on behalf of the USSR Academy of Sciences was given by F V Bunkin, who remarked on the key role of academic science in elaborating the physical principles and in developing unique electron-optical instruments for quantum radiophysics and nonlinear optics. The congress proved that in the field of image-converter photonics Soviet science held the leading position.

5. High-speed photoelectronics abroad and international cooperation

In 1958, at the 4th International Congress on High-Speed Photography held in Cologne (FRG), the Kurchatov Institute of Atomic Energy, Moscow presented a series of reports that described Soviet image-converter tubes and cameras specially designed for recording fast processes for the first time [11, 22]. At that time Westinghouse and RCA had only begun developing time-analyzing ICTs with a grid gate and a pair of deflection plates [71]. Later these tubes were used to build commercial STL\TRW-type cameras for framing recording and linear sweep with subnanosecond time resolution. These cameras were produced until the mid-80s and were equipped with biplanar-type image intensifiers with optical-fiber disks.

In 1972, S Thomas, L Coleman and coworkers at the Lawrence Livermore Laboratory reported on the development of a 10-ps image-converter camera intended for research in laser-induced controlled fusion [72]. The camera was built around a standard RCA tube, with a set of avalanche transistors used to form the sweep pulses.

British specialists were so amazed by the Soviet time-analyzing ICTs presented at the Cologne conference that they decided to copy them [73]. In 1962, Associated Electrical Industries produced the first prototype of an image tube, and A Huston built a multiframe system around it with a recording rate of 2×10^7 frames per second and a minimum frame exposure of roughly 10 ns [74]. In 1965, Telford Ltd. manufactured a small batch of such cameras. Soon after, the British (and later on the world) market became dominated by J Hadland Photographic Instrumentation with its Imacon brand cameras (Imacon-700, 600, 675, and 500). The first cameras of this make permitted 16-frame high-speed recording of fast processes with a rate up to 6×10^8 frames per second and a time resolution of 25 ps in the streak mode. Since 1968, D J Bradley's group at Queen's University, Belfast in Northern Ireland became actively involved in this work. Later, the group moved to Imperial College, London. In 1970, Bradley ordered an accelerating grid to be put inside a P856 tube produced by the English Electric Valve Co. (the tube was an analog of the Soviet PIM-3 tube) [75]. The new image tube, which became known as the Photochron, recorded (in 1972) 1.8-ps pulses of light generated by a 615-nm laser that operated on a Rodamin-6G dye with passive mode-locking. Here, the sweep speed was 1.1×10^{10} cm s^{-1}, and the electric field strength at the multialkali photocathode reached 800 V mm^{-1}. In 1975, Sibbett, Ruddock and Bradley [76] reported recording 0.9-ps light pulses generated by a continuous-wave laser that operated on the Rodamin-6G dye with passive mode-locking (sweep speed 2×10^{10} cm s^{-1}, electric field intensity at photocathode 2 kV mm^{-1}, photocathode S20, and single-photon recording mode).

In 1961, the French company Thomson – Houston developed its first THX410-type time-analyzing ICT with a grid gate near the cathode and two pairs of deflection plates [77]. Later, in France [78] and in the United States [79], devices were developed for a circular image sweep, with the French Picoscope having capacitor-type deflection plates and the American device, a 3-GHz travelling-wave deflecting system.

In the mid-70s, the Japanese company Hamamatsu entered the design stage in the production of ultrahigh-speed electron-optical equipment, and in 1980 the company produced a commercial image camera with a 2-ps time resolution, a built-in multichannel plate, and a TV system for reading images off the ICT screen [80].

It should be emphasized that the high level of Soviet image-converter instrument making attracted much attention from foreign science centers and companies. The native scientific community in this field saw cooperation with foreign countries as a means of upgrading quality of our own devices and bringing about joint production of cameras with a view to providing our research centers with a sufficient supply. For instance, from 1972 to 1976, according to the plans of cooperation in science and technology drawn up by the Soviet – French Commission on Instrument Making, batches of TSN brand picosecond cameras developed by Thomson – CSF were tested at FIAN on laser test benches [81]. Firstly, two methods of recording images from the screen of a time-analyzing ICT were compared: via a Soviet multistage image intensifier, and via a French image intensifier built around a THX496 brand microchannel plate. As a result, for the first time it was shown through experiments that the use of MCP image intensifiers in developing picosecond streak cameras for laser studies was a promising feature. Another important result of this cooperation was the first evidence of the advisability of replacing film with a highly sensitive TV tube and then recording the image on a video recorder for further visualization on a TV display.

The cooperation with the British company DRS – Hadland, which started in 1967 and is still going on, proved to be the most fruitful and long-term. The agreement about joint production of picosecond image-converter cameras, signed with this company by officials of the USSR State Planning Commission, accumulated the experience of many years of development of a new generation of PV image tubes in the Soviet Union and the company's experience in building control circuits and designing image-converter cameras of a broad appointment. The result of this collaboration was the Imacon-500 camera. Over a hundred cameras of this brand were manufactured, and in the twenty years that have passed, all of them have worked very reliably both in Russia and abroad, ensuring photographic recording of fast processes with a time resolution of order 1 ps in the 110 – 1550-nm spectral range (Fig. 10a) [82]. At present IOFAN is continuing, within agreements on R&D with DRS – Hadland, the joint development of time-analyzing ICTs (e.g. the PF brand, where PF stands for femtosecond image converter in Russian), which are installed in the famous 468 model British cameras which in 1999 received the Royal Award for the Technological Achievements.

During the period of intensive cooperation in R&D with the Japanese company Hamamatsu (1978 – 1986), a joint image-converter recording system built around the Soviet-made PV-001 tube and the Japanese TV readout system C1330/C1440 was developed [83]. Its maximum time resolution was 1.4 ps at $\lambda = 610$ nm with a streak speed of 5×10^9 cm s^{-1} and a dynamic recording range of about 70. The image from the ICT screen was fed to a computer in

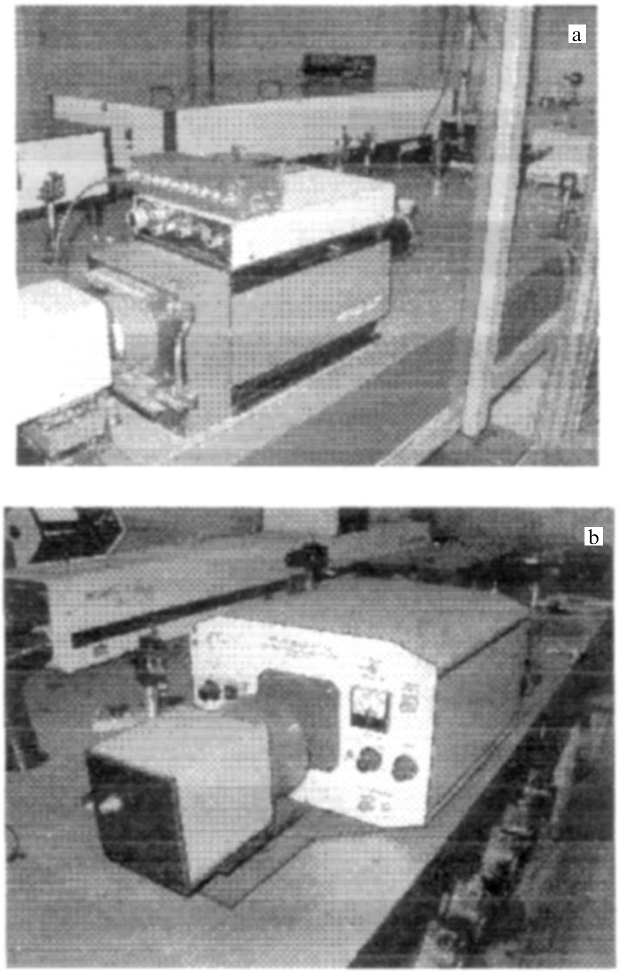

Figure 10. Jointly developed streak cameras: Imacon-500 (DRS–Hadland) (a), and PROSCHEN (Cordin) (b); the cameras were built around the Russian-made PV tubes.

$256 \times 256 \times 12$-bit format for further processing and data analysis.

Another example of stable and long-term cooperation are the studies that are being conducted jointly with the Cordin instrument making company of the United States [84]. The result of this cooperation was the design and production at the beginning of the 1990s of a batch of picosecond streak cameras built around the Russian-made PV tubes. The cameras operated in the single linear-sweep mode and in the synchronous scan mode (the scanning frequency was 320 MHz) (Fig. 10b).

As a result of cooperation in R&D with V-TEK (Republic of Korea), at the beginning of the 1990s IOFAN manufactured a new PIF brand compact tube (PIF stands for pulsed femtosecond image converter in Russian), which was later used in jointly developing and producing a small batch of picosecond cameras [85]. In the linear-sweep mode these cameras ensured a resolution no worse than 10 ps. The image from the ICT screen was recorded by a CCD sensor interfaced with a computer.

The same period has seen a most fruitful cooperation with the Institute of Fine Mechanics and Applied Optics (IFMAO) (Sian, People's Republic of China). In 1988, IOFAN and IFMAO published the results of computer simulation of a 50-fs ICT that had a cylindrical electrostatic lens and a jointly patented compensator of the angular spread of the photoelectron initial energies [86]. The very first tests of the experimental ICT with a cylindrical lens produced encouraging results. Even without the compensator the time resolution of the ICT was 500 fs, with an electric field strength at the photocathode of 6 kV mm^{-1} and a linear-sweep speed of 1.7×10^{10} cm s^{-1}.

In 1989, the construction of a stable $YAlO_3:Nd^{3+}$ solid-state laser with hybrid mode locking and passive intracavity negative feedback utilizing a GaAs plate in its cavity was completed [87]. The laser generated, with a frequency of several hertz, microsecond trains of pulses with a duration of 5 ± 1 ps and an output-energy instability of approximately $\pm 1\%$ at $\lambda = 1.08$ μm. After the passage of an optical-fiber compressor, the minimum duration of single pulses measured by an autocorrelator was found to be 300 fs.

At the end of the 1980s, a series of experiments was conducted jointly with the Scientific Instrument Making Center in Berlin (Germany) [88]. The researchers tested an image-converter tube (designed by German scientists) with a built-in silicon target for direct conversion of time-dispersed photoelectronic images to electric signals for subsequent input into a computer. In the same period, researchers at IOFAN put into service, together with researchers from Jena University (Germany), a continuous-wave Rodamin-6G dye laser operating on the colliding-pulses principle [89]. The laser, which produced single shots approximately 90 – 120-fs long at $\lambda = 610$ nm, was used to measure the temporal instrument function of the PV-001 device in a direct experiment, and the halfwidth of this function proved to be 900 fs [90]. When the photocathode was illuminated with pulses 500-fs long from a $LiF:F_2^-$ crystal laser, the temporal response function narrowed down to 700 fs. The laser was developed in cooperation with V V Osiko, T T Basiev and others (see Ref. [91]). The two experiments took place under the following conditions: an Ag – Cs – O photocathode, an electric field intensity of 3 kV mm^{-1}, a sweep speed of $(1.6-2) \times 10^{10}$ cm s^{-1}, and the image recording through a MCP image intensifier with a conversion factor of 3×10^4 using a TV readout system.

It must be said that the end of the 1980s and the beginning of the 1990s was the most intensive period in international contacts in R&D. Together with Prague Technical University (Czechoslovakia), new picosecond streak cameras with a circular sweep intended for laser probing of the atmosphere were developed and studied [92]. Jointly with Campinas University (Brazil), the Russian-made streak cameras were used to study optical-fiber erbium IR lasers ($\lambda = 1.55$ μm), which were intended to be used in super fast optical-fiber communication links [93].

By this time the work in optical fiber optics was in the lead at IOFAN. For instance, under the aegis of E M Dianov research was being done in observing, using ICTs, the light amplification in the process of the nonlinear interaction of counterpropagating waves in a single-mode optical fiber [94]. The decay of picosecond light pulses in the course of self-switching of light in tunnel-coupled waveguides was observed in ICT experiments by Maĭer et al. [95].

Striking experiments were conducted by L A Kulevskiĭ and coworkers (see Ref. [96]), who observed the nonlinear photoresponse in the process of image-converter recording of picosecond pulses generated by an erbium laser ($\lambda = 2.94$ μm). The pulses of light at the fundamental frequency and the second (1.47 μm) and fourth (0.73 μm) harmonics were fed to an input of the ICT with a silver – oxygen – cesium photocathode that had a photoemission threshold of 1.3 μm. The minimum length of the pulses recorded by the ICT at the fourth harmonic was 60 ps with an input power density of $\leqslant 10^3$ W cm^{-2}, at the second harmonic the minimum pulse length was 80 ps with an input power density of 10^6 W cm^{-2}, and at the fundamental frequency the minimum pulse length was 45 ps with an input power density of 10^8 W cm^{-2}. The researchers also found the order of nonlinearity of the photoresponse, which amounted to 2.6 ± 0.3 (at 2ω) and 4.6 ± 0.5 (at 4ω).

Thus, by the end of the 1980s, picosecond electron-optical diagnostics reached the peak of its instrumental perfection due to the use of new-generation ICTs, semiconductor subnanosecond high-current switches, optical-fiber and microchannel plates, and CCD-sensor readout cameras. The international cooperation organized by A M Prokhorov and the regular exchange of information at the International Congresses on High-Speed Photography and Photonics contributed very largely to the development of this field of research. However, the question of the attainable time resolution of ICTs, which was barely 1 ps at that time, remained. Such ICTs were no good for direct measurements of the intensity profile of femtosecond pulses (< 100 fs) or for photographing fast processes initiated by such pulses. Where will the development of ICTs lead to in the near future?

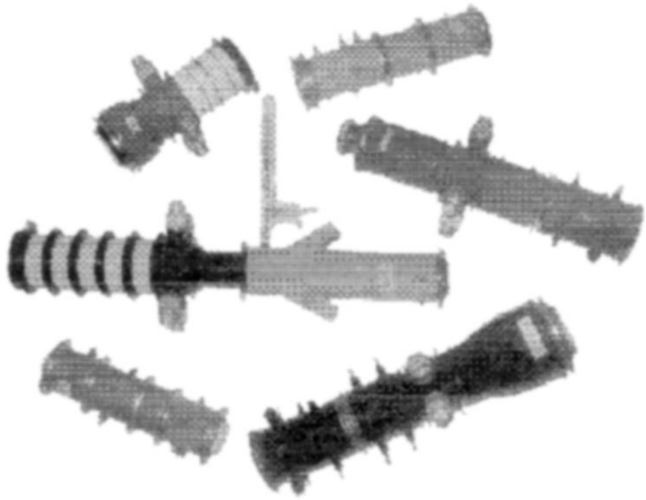

Figure 11. Pico-femtosecond ICTs designed and fabricated at IOFAN.

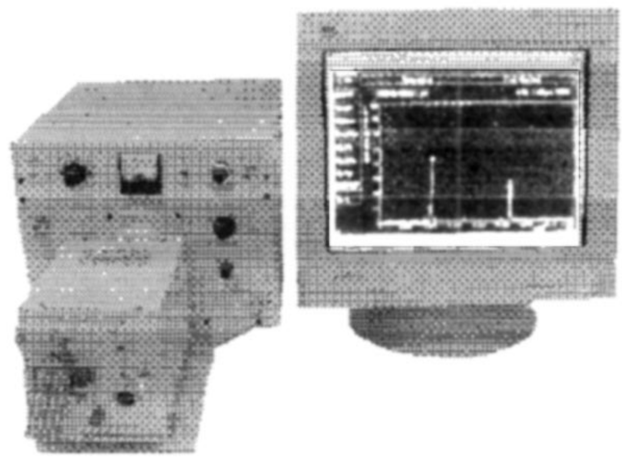

Figure 12. 400-fs synchroscan built at IOFAN.

6. Femtosecond diffractometry

The answer to this question was given by further events. By the beginning of the 1990s there was a downward trend in the development of applied science in Russia, and it became more and more difficult to order time-analyzing ICTs at VNIIOFI. This forced A M Prokhorov, the Director of IOFAN at that time, to organize full-scale studies in femtosecond photoelectronics in the IOFAN Photoelectronics Department. This led to the formation of a compact, highly adaptable and closed-up technological chain for designing and manufacturing experimental samples of pico-femtosecond ICTs and cameras based on them. This chain encompasses all the production cycle: from working-out the design specifications, through computer modelling and computer-aided design to the technological support of optomechanical, glass-blowing, welding, chemical-engineering, and vacuum-pumping jobs, to the production of photocathodes and phosphor screens, and, finally, to the manufacture of the end product followed by its static and dynamic calibration done on laser test benches at IOFAN. This R&D work chain is still functioning, ensuring the fabrication of time-analyzing ICTs (of PIF, PF, and PV brands) competitive world-wide (Fig. 11) [97]. Following are the parameters of the ICTs being developed: the size of photocathode's entrance area is 4×20 mm^2; the spatial resolution referred to the plane of the input photocathode is 30 – 50 line pairs per millimeter; the photocathode-to-screen optical-mapping scale is 0.7 – 2; the spectral sensitivity range spans 115 – 1600 nm; the equivalent illuminance of dark background is no greater than 10^{-7} lm cm^{-2}, and the maximum time resolution is 0.4 – 0.5 ps. This time resolution was measured by cameras built around the above ICTs, which operate in the streak mode with a sweep speed of $(1-2) \times 10^{10}$ cm s^{-1} [98] and synchronous scan by a sinusoidal voltage with a frequency of 320 MHz (Fig. 12) [99].

In order to dynamically calibrate ICTs and ICCs, the Photoelectronics Department commissioned a sapphire-titanate-based laser system that generates a train of single 60-fs pulses at a repetition frequency of 82 MHz. After a positive-feedback amplifier the energy of the single 120-fs laser pulses became 1 – 2 mJ at a repetition frequency of 10 Hz. The second-harmonic oscillator (a KDP crystal), the fourth-harmonic oscillator (a BBO crystal), and the travelling-wave parametric oscillator operating together make it possible to generate optical pulses of femtosecond duration in the spectral range from 210 to 1600 nm [100].

Modern research in femtosecond electronics is characterized by the support given to, and advancement of, the theoretical and software bases for computer simulation of time-analyzing ICTs and by the development of own application packages used in designing new devices [101]. The electrolytic baths used in the 1960s and 1970s to model electrostatic fields have been replaced with powerful modern computers that permit thorough calculations of the parameters of the images formed by electrostatic and magnetic lenses with any configuration of the electrodes.

Today new research is being carried out in the physics of interactions of pico-femtosecond light pulses and classical photocathodes. It is known that the time delay of the electron packet, determined by the halfwidth of the photoelectron distribution over the initial energies, $\Delta\varepsilon$, depends on many factors, among which are the photocathode's material and thickness, the intensity and wavelength of the incident radiation, the electric field strength at the photocathode, and the type of illumination (direct or rear). Vorobiev et al. [102] showed in their direct experiment that for Ag – Cs – O photocathodes with a surface resistance of $10-100\ \Omega\ \mathrm{cm}^{-2}$, manufactured at the Photoelectronics Department, $\Delta\varepsilon \sim 0.1$ eV at $\lambda = 1550$ nm and broadens to 2 eV at $\lambda = 395$ nm. The search is on for new, more sensitive, photocathodes in the near IR region. For instance, Nolle et al. [103] used an InGaAs/InP/Ag(Au) Schottky-barrier heterostructure grown by the molecular beam epitaxy (MBE) to fabricate a negative-electron-affinity (NEA) photocathode with a sensitivity at $\lambda = 1.55$ μm that is more than two orders of magnitude higher than the sensitivity of the best silver – oxygen – cesium photocathodes. Earlier the MBE method was implemented to grow multialkali photocathodes with highly reproducible parameters and a quantum efficiency of up to 40% at $\lambda = 400$ nm [104].

Bryukhnevich et al. [105] made an extensive study of the problem of replacing the luminescent screen in ICTs with an electron-sensitive CCD sensor, accompanied by direct input of time-dispersed photoelectronic images into a computer. A camera built around such an image tube was found to have a high sensitivity (10^{-10} J cm^{-2}) and a high spatial resolution (more than 40 line pairs per millimeter over the photocathode).

The experience in R&D gathered in recent years has made it possible to initiate new explorations on the base of electrooptical devices with pico-femtosecond resolution. For instance, the staff of the experimental facility of the IOFAN Photoelectronics Department is conducting a series of experiments aimed at building an optical femtosecond tomograph, a device that will allow one to determine, to within fractions of a millimeter, the position and geometric configuration of any inclusions in biological tissues. One crucial problem in building such tomographs is the separation, in space and time, of the nonscattered ballistic photons from the photons scattered by the biological medium. Ballistic photons play an important role in forming the image of an object that intensively scatters light. To observe the two kinds of photons separately in time, the duration of the probing laser pulses must lie in the femtosecond range, and the recording equipment must guarantee an appropriate time resolution and be highly sensitive. Vorob'ev et al. [106] used diluted milk as a model of a strongly scattering medium and found the experimental conditions needed for successful time resolution of the two kinds of photons.

In 1991, A Zewail proposed that the Photoelectronics Department should develop a femtosecond photoelectron gun for conducting experiments aimed at establishing the fundamental properties of matter by studying the dynamics of chemical reactions in various substances [107]. Several angstroms and femtoseconds are the spatial and temporal scales on which processes involved in the transformations of chemical bonds (the formation and/or breaking of such bonds) take place. This means that atoms may collide, interact, and form new molecules in the course of several tens of femtoseconds. With the fabrication of a femtosecond diffractometer it becomes possible to study the kinetics of such molecular transformations.

The elastic interaction of a well-collimated (beam divergence $0.1-1°$) ultrashort pulse of monoenergetic ($0.1-1$ eV) electrons accelerated to $20-40$ keV and the atomic – molecular structure of the substance investigated is determined primarily by the electrostatic potentials of the constituent atoms, with the peaks in these potentials coinciding with the positions of the atomic nuclei. The Fourier transform of the intensity distribution in the diffraction patterns is directly proportional to the probability density of the interatomic distances within an individual molecule. The incident electrons lose very little energy when they elastically interact with the electrostatic fields of the atoms, with the result that on the whole the energy state of the atomic – molecular system remains almost unchanged. Furthermore, according to estimates the typical time of an elastic electron scattering event is much shorter than 1 fs. All this suggests that femtosecond photoelectron diffraction constitutes a direct method of recording the atomic – molecular dynamics of matter. The problem lies in the creation of a femtosecond source of electrons operating in synchrony with the femtosecond laser pulse used to excite the sample and to ensure the formation and recording of the time-dispersed diffraction patterns.

In 1982, Mourou and Williamson [108] used electron flashes (100 ps, 20 keV) generated in a time-analyzing ICT and observed, for the first time, the electron diffraction pattern from an aluminium film 150-Å thick by transillumination. Bryukhnevich et al. [109] also attempted to use a femtosecond photoelectron gun of a time-analyzing PV-001 ICT for their diffractometer, but after several attempts it became evident that only a specially designed device could combine the functions of an ICT (generation and measurement of the duration of a photoelectron beam) and the electron diffraction functions (the formation of an electron beam with the requisite divergence and of the diffraction patterns).

The first femtosecond electron diffraction gun was computer designed with a software package developed at the Photoelectronics Department of IOFAN, and in 1996 it was assembled and tested [110]. The gun provided formation of a photoinduced, monoenergetic (energy spread less than 0.5 eV), well-collimated (angular divergence smaller than 0.5°), sharp (diameter of target spot was smaller than 0.7 mm at the $1/e$ level), and ultrashort (shorter than 500 fs) bunch of $(15-30)$-keV electrons to be used for time-resolved electron diffraction (TRED). In single-shot mode, it generated up to 10^3 photoelectrons, and the electron pulse profile could be measured in streak mode on the gun's screen (Fig. 13). A solid-state target was then placed in the crossover region, with a diffraction pattern forming on the gun's screen when the target is under transillumination. In synchrony with the transilluminating electron pulse the target was illuminated by exciting laser radiation. The result was a 'respiring' diffraction pattern. By selecting the proper delay time between the exciting laser pulse and the transilluminating electron pulse one can photograph the diffraction patterns corresponding to different moments in the state of the target's material. Figure 14a illustrates the operational principle of the femtosecond diffractometer developed at the Photoelectronics Department, and Fig. 14b depicts the general view of the diffractometer camera. Theoretically, the processing of the time bases of the diffraction patterns provides information about internuclear distances, molecular temperature, atomic movements, phase transitions, and lattice perturbations.

Demonstration experiments that would verify the operating parameters of the new diffractometer were conducted in

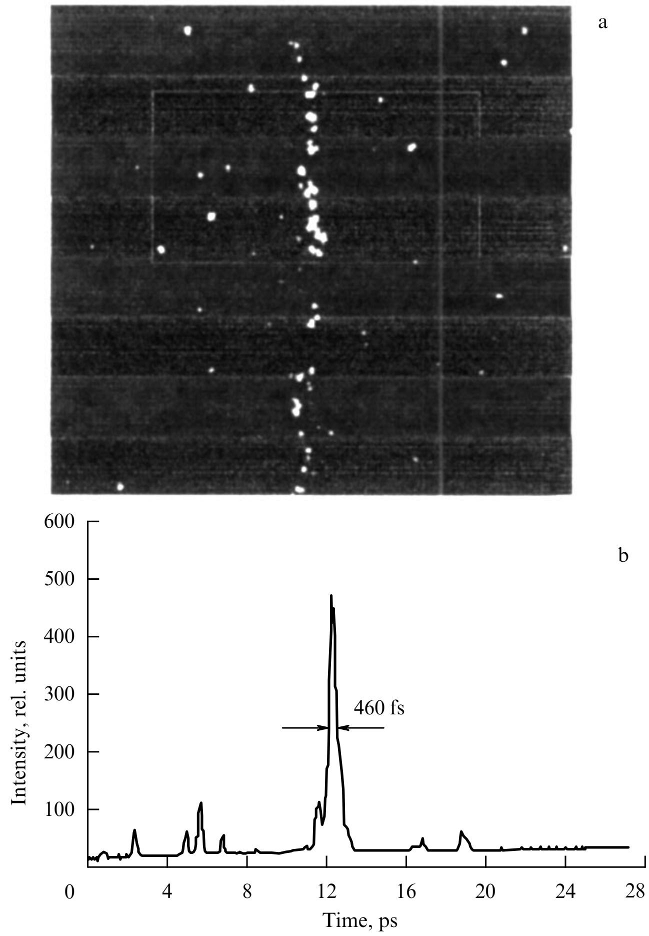

Figure 13. Image of a photoelectron pulse ~ 500-fs long (a), and the corresponding densitogram (b).

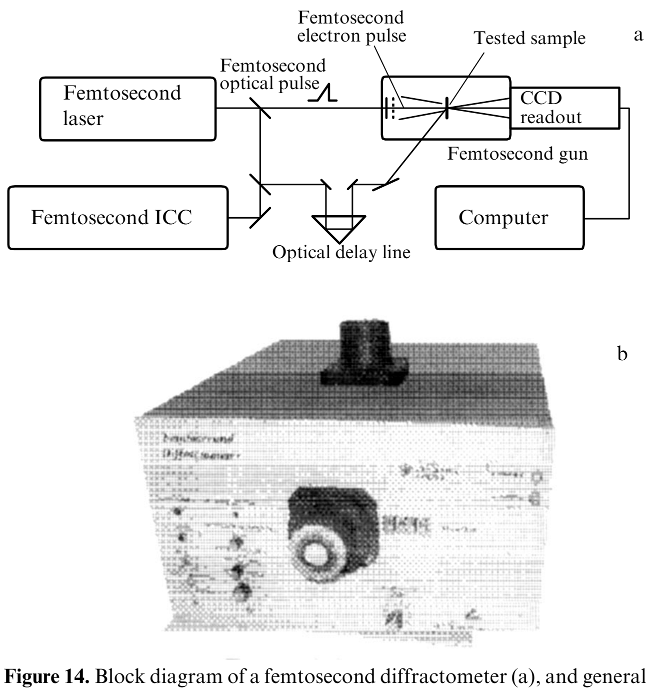

Figure 14. Block diagram of a femtosecond diffractometer (a), and general view of the diffractometer camera.

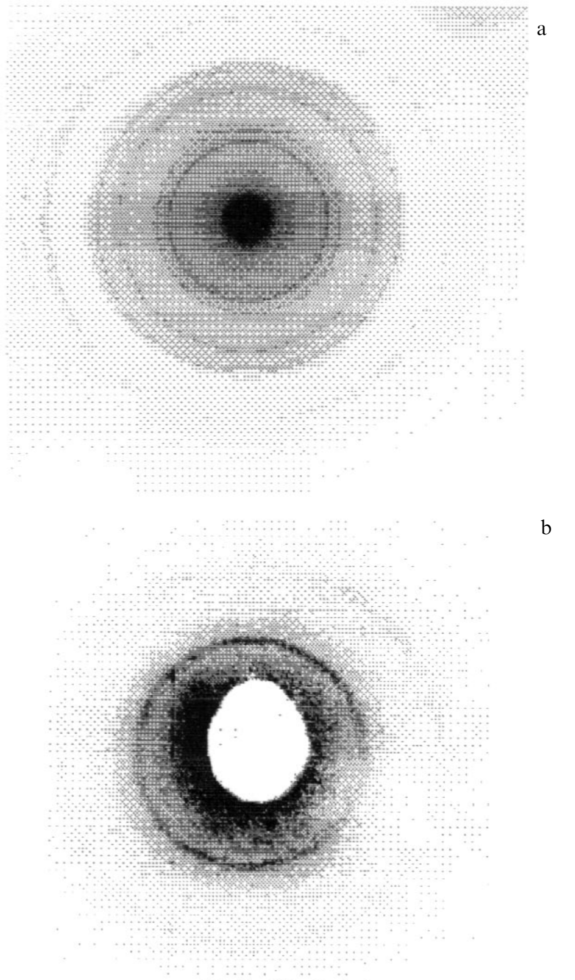

Figure 15. Diffraction pattern from a 300-Å thick Al film captured by a standard electron diffractometer (a), and by a 500-fs photoelectron diffractometer (b).

V V Klechkovskaya's laboratory at the Institute of Crystallography of the Russian Academy of Sciences with a standard electron diffractometer and a 300-Å thick Al foil in transmission mode and resulted in static diffraction images of reasonable quality. The film was first transilluminated with a 30-keV electron beam for 7 s with a 50-μA current (Fig. 15a). Then the sample was placed inside the photoelectron diffractometer and a diffraction pattern was recorded (Fig. 15b) during the accumulation of 4×10^4 500-fs photoelectron pulses following at a repetition rate of 82 MHz and containing roughly 10^3 electrons per pulse. The position of the diffraction rings was used to determine the lattice constant of aluminium, which was found to coincide perfectly with the tabulated data.

Thus, the new device made it possible to record diffraction patterns with a time resolution of 500 fs. This means that the operation speed of the photoelectron diffractometer is almost thirteen orders of magnitude higher than that of standard electron diffractometers. Notice that under the conditions of the above experiment the thermal emission gun of the electron diffractometer emits roughly 10^{14} electrons every seven seconds, while the total number of photoelectrons emitted by the input photocathode of the photoelectron diffractometer does not exceed 10^8 electrons for every 4×10^4 flashes (the accumulation time was about 2×10^{-8} s). This suggests that the sensitivity of the photoelectron diffractometer is extremely high, with the images obtained being of reasonable quality.

7. Conclusions

High-speed electron-optical photography has developed very dynamically for almost 50 years, closely following the trends and needs first of nuclear physics, then laser physics and optics, and, finally, physical chemistry and biomedicine. The new requirements imposed on the recording electron-optical equipment always originated in the physical problems being solved. Here the high-speed image-converter instrument making was based on well-researched physical principles and was marked by a keen ability to absorb the experience gathered in related areas of research.

With the development of such areas of modern science and technology as optical-fiber communications, femtosecond information technology, laser-induced controlled fusion, bio-medicine, and ecology the need for unique measurement and diagnostic facilities increases dramatically. This is strikingly confirmed by the use (in physical chemistry) of a modified ICT as a diffractometer gun in studies of matter behavior at the atomic–molecular level. An important aspect in the application of these studies is the possibility of producing materials with predefined properties. The improvements introduced into ICTs operating as diffractometers and the development of ways in which these devices can be used constitute a separate, fairly complicated problem related to many investigations in such areas of research as electric breakdowns in vacuum and gases, and in the technological problem of developing high-voltage pulsed power sources. Another important problem here is the writing of an adequate software for analyzing and processing the patterns on the diffractometer's screen, aimed at extracting quantitative information about the relevant processes.

There are rather many problems in the development of the methods of electron-optical recording that are still awaiting solution. Among these is the following question of a fundamental nature: Can a 10-fs time resolution be achieved in practice? Today the best Russian and foreign-made photorecorders have a maximum time resolution of 180–500 fs [111, 112]. It should be notable that in such photorecorders the electric field strength at the photocathode has been raised by a factor greater than 100 (from 60 V mm^{-1} to values larger than 6 kV mm^{-1}) and the component of the time resolution related to the chromatic aberrations of the electron lens must not exceed 100 fs. This example clearly shows that many different factors (more than ten) affect the limiting time resolution. And even if the contribution of each of these factors is confined to 10 fs (according to the earlier estimate of Zavoĭskiĭ and Fanchenko [13]), their total effect can lower the expected limiting time resolution severalfold. On the whole it is clear that rigorous analysis and experimental verification of the contribution to the time resolution of not only each factor alone, but of all the factors together are necessary.

Solving all these problems and the problems that are sure to emerge in the future, since it is impossible to halt scientific thought and the quest for knowledge, will require the enthusiasm of youth, the wisdom of maturity, and at least a ray of hope that the research discussed in this report will be needed in the near future of Russia.

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Scientific instrument making in space exploration

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1. Introduction

Just a little over four decades ago the first Soviet space probes (SPs) launched to the Moon, Venus, and Mars started a new stage in the exploration of bodies of the solar system other than Earth by spacecraft. In this period a huge volume of entirely new scientific data has been gathered, which has made it possible to make considerable progress in developing mankind's knowledge about the surfaces of these bodies, their crusts, and their inner structure.

In a report so brief there is no hope of giving a full account of the progress made in scientific instrument making over the years. Therefore the report focuses on the three main trends in scientific instrument making in space exploration, the trends to which the Soviet and post-Soviet scientists contributed the most in their exploration of the Solar system.

2. Building of scientific instruments and experiments in exploring the Moon and the planets

The design of onboard scientific instruments and the preparation for scientific experiments began in the 1950s at the V I Vernadsky Institute of Geochemistry and Analytical Chemistry (GEOKHI in Russian) of the USSR Academy of Sciences at the same time that preparations began in our country for launching space probes to the Moon, Venus, and Mars. The Academy of Sciences and later the Soviet government decided to make GEOKHI the leading organization in studies of extraterrestrial matter by space probes and of samples of such matter brought to Earth by the probes. From that time on, practically all space probes that flew to the Moon, Venus, and Mars carried equipment designed and built at GEOKHI with which numerous experiments were implemented.

Here is a list of space probes that were used by the staff of GEOKHI to carry out the most successful experiments: Luna 10, Luna 12, Luna 16, Luna 20, Luna 24, Venera 4, Venera 5, Venera 6, Venera 8, Venera 9, Venera 10, Venera 12, Venera 13, Venera 14, Vega 1, Vega 2, Mars 5, Phobos 1, Phobos 2, Salyut 7, and Mir.

The devices designed at GEOKHI and mounted on these space probes were intended for determining the chemical composition and the physical properties and structure of rocks, for studying the atmosphere and cloud layer of Venus, for gathering and analyzing cosmic dust, and for other purposes. Various models of mass spectrometers, gamma-ray and X-ray spectrometers, conductometers, densimeters, moisture meters, and other instruments were used.

The first onboard devices were relatively simple and produced little information. The reason for this was that at the time there were no solid data for designing and building devices. For instance, unknown were the basic composition of the Venusian atmosphere (the composition determines the g-loads that the SP experiences when it enters the atmosphere) and the strength of the atmosphere (this led to the loss of the first space probes landing on Venus before they even reached the surface), and nothing was known about the surface of Venus (whether it was liquid or rocky), so that by analogy with Earth the first descent modules were designed for landing in an ocean. However, even the results of the early voyages to Venus of space probes with landing modules (Venera 4, 5, and 6) suggested that the planet's surface shows evidence of being incandescent desert (with temperature close to 500 °C), and that the atmosphere at the surface is mainly carbon dioxide at a pressure of about 100 atm. The results of each of these pioneering flights to Venus brought about many discoveries and explained the differences between Venus and Earth — planets that in many other parameters are quite similar.

In time the devices used in space exploration became more sophisticated and the number and the range of problems covered by experiments increased dramatically. Detailed studies of the surface of Venus were on the agenda. The space probes Venera 8, 9, and 10 were first to land on the Venusian surface and in the extreme conditions mentioned earlier determined, through the use of the earliest Venusian gamma-ray spectrometers built at GEOKHI, the type of rocks by the abundance of natural radioactive elements such as uranium, thorium, and potassium. The time finally came for carrying out probably the most complex studies of Venus, i.e. determining the elemental composition of Venusian rock on the planet's surface. This problem was originally solved by the Venera 13 and 14 descent modules, whose landing sites were in flatlands, and later by the Vega 2 space probe, which ejected a balloon-borne instrument package that landed in the Aphrodite mountainous area. In order to determine the composition of Venusian rocks, a soil-sampling device took samples of rocks. These samples were automatically placed into hermetically sealed bays of the landing module and later