Miniaturization of high-speed streak cameras for fast running processes recording

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Abstract

The review of development of image converter instrumentation in All-Russian Research Institute for Optical and Physical Measurements (VNIIOFI) is resulted from the moment of institute formation on the present in respect of miniaturization of high-speed cameras from their first generation to the last - the third. The cameras of the third generation are operating in streak mode and multi-frame mode, as well as in single-frame mode.

Temporal registration range covers interval from subnanoseconds (with limiting temporal resolution in picoseconds) to tenths of seconds. Spectrum range covers the whole interval from soft X-rays to near infrared. All cameras can be controlled remotely through fiber optic cable.

Provided software allows correction of all kinds of geometric and photometric image distortions, creating temporal and spatial profile of the image brightness, measuring speed and carrying out many other image processing functions.

Key words: image converter tube, camera, fast running processes, sweep, spatial and temporal resolution.

1. STREAK CAMERAS OF THE FIRST GENERATION

An image converter method of registration and measurement of parameters of fast running processes exists already 67 years. The first successful attempt to sweep in time the electron beam moving from the photocathode to the screen of the image converter tube was carried out by Courtney–Pratt in 1949 (1). The sweep was carried out by a pulsed magnetic field. The first-ever in the world image converter streak tube PIM-3 with sweep of the image by electric field has been created in Soviet Union in 1949 by M.M. Butslov (2). Later (in 1962), streak tube of FE-9A, similar to the Russian PIM-3, was created in England(3). Attempts to use these tubes in streak cameras for achievement of the high temporal resolution have shown that one of the main factors limiting the temporal resolution is Coulomb repulsion of electrons near the photocathode due to their high density. Brightness intensification of the image already swept on the screen of these tubes has been applied for essential decreasing density of electrons near the photocathode. Strong enough magnetic field created by usually heavy solenoid was used for focusing electrons in the brightness intensifiers of that time.

Therefore, FER-2 streak camera with 20 ps limiting temporal resolution created in the Soviet Union in VNIIOFI in 1966, i.e. in the year of Institute foundation, was very heavy. It had weight of ~ 250 kg, highly imposing dimensions 2200 x 450 x 710 mm and its power consumption was about 1 kVA. An element base of electronic components at that time (necessary for creating stabilized current sources, stabilized high-voltage sources power-supplying tube's electrodes and lamp pulse circuits) also had large over-all dimensions, heavy weight and high power consumption. All these components have been placed in a powerful cast construction of the FER-2 camera, which has begun the first generation of high-speed cameras of VNIIOFI (Fig. 1).

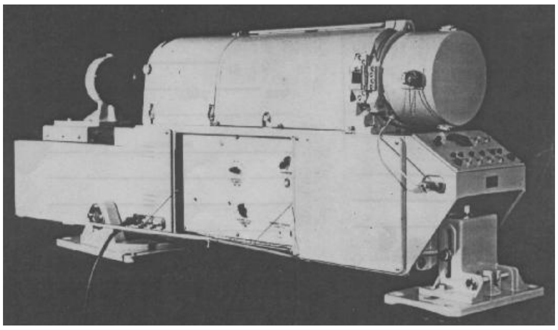

Fig. 1. FER-2 streak camera.

For example, English Imacon 600 camera with 10 ps limiting temporal resolution of Hadland Photonics LTD Co. for the same reasons also was rather bulky with big consumption, but maybe a little more convenient in configuration (fig. 2).

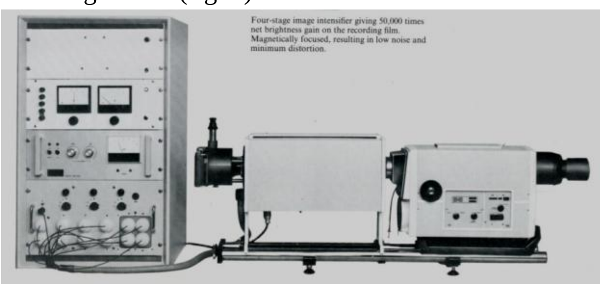

Fig. 2. Imacon 600 camera (1970): size of the recording part 1950x250x500 mm, racks - 530x560x890 mm, total weight of ~210 kg (the recording part ~115 kg, rack 94 kg), consumption 1 kVA, water cooling of the solenoid at long work.

It should be noted that in all cameras of the first generation an image of registered process was recorded on photo film.

2. STREAK CAMERAS OF THE SECOND GENERATION

With the emergence of vacuum-tight fiber-optical plates (FOP) at the 2nd half 70th years of 20th century, and then also microchannel plates (MCP) for amplifying electronic streams, dimensions of the streak tubes were sharply reduced, because the necessity in the intensifiers with magnetic focusing of electrons has disappeared. Also thanks to progress in miniaturization of electronic components, rather small-sized for that time C979 streak camera with temporal resolution of 10 ps was designed by Japanese Hamamatsu Company in 1978 (Fig. 3). It had size comparable to the size of desktop oscilloscopes of that time.

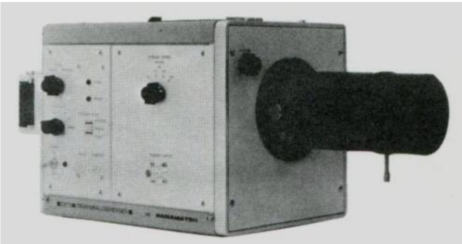

Fig. 3. C979 streak camera of the Japanese Hamamatsu Company, 1978: size ~ 600x250x300 mm, weight ~ 22 kg, consumption ~ 80 VA.

Similar compact streak camera Agat-SF1, designed in same year (1978) in VNIIOFI (Fig. 4), had 2 ps temporal resolution. Agat-SF1 was the beginning of the second generation of VNIIOFI cameras.

Fig. 4. Camera Agat-SF1 on a support: size 903x202x388 mm, weight of 30 kg, power consumption 100 VA.

After a while cameras of a similar class appeared in England (Imacon 675, Imacon 500) and in France (TSN 506). Thus, emergence of FOP and MCP initiated breakthrough in creation compact streak cameras at all producers.

Digital systems for recording and processing of the recorded image appeared in many models of the second generation streak cameras.

3. STREAK CAMERAS OF THE THIRD GENERATION

In 1997, the BIFO company developed miniature low-voltage PV-201 streak tube with integrated MCP and one pair of deflecting plates (Fig.5), and then PIM-112 tube also with one MCP, but with two pairs of deflecting plates (Fig. 6).

Fig. 5. Miniature PV-201 streak tube, used in the K008 camera (has one MCP): photocathode S20, length 78 mm, width/diameter is 60/48 mm, weight 0.45 kg.

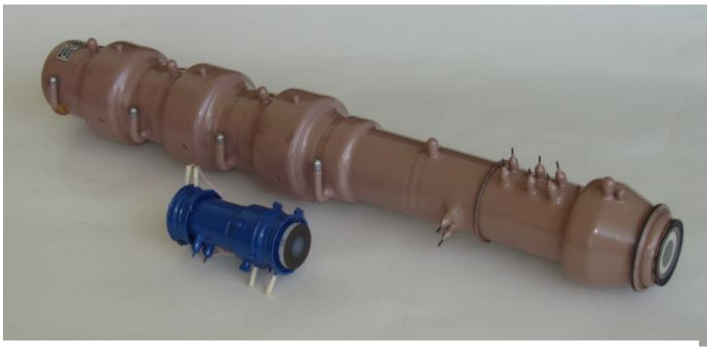

Fig. 6. UMI-93 streak tube of the first generation, which includes a built-in three-stage brightness intensifier with magnetic focusing (the focusing solenoid is not shown) and PIM-112 tube of the third generation with electrostatic focusing and built-in MCP.

PIM-112's main parameters are not worse than parameters of the UMI-93.

In 1998, miniature and low power consumption K008 camera was designed on the basis of PV-201 tube by VNIIOFI together with the BIFO Company [(4)]. Camera was presented at the exhibition of the 23rd International Congress on High-Speed Photography and Photonics in Moscow. It worked both in single-frame mode (frame duration is from 10 ns up to 600 μs), and in the streak mode with sweep duration from 2 ns up to 600 μs. Cameras of the second generation, produced in the 1980s, had weight of dozens of kgs and consumed about 100 VA. For instance, a widely known Agat-SF1 picosecond streak camera. In accordance with the trends of the new time, most of the third generation cameras, are significantly smaller in size (Fig. 7), have weight only of several kilograms and consume several units of VA [(5)].

Fig. 7. Streak cameras of the second and third generations. Right: Agat-SF1 camera: 2 ps limiting temporal resolution, photofilm image recording; dimensions 903x202x388 mm; weight: 30 kg; power consumption 100 VA. Left: the first model of K008 camera: 50 ps limiting temporal resolution, dimensions 335x90x190 mm; weight 3.5 kg; power consumption 8.5 VA, RU-02M CCD camera – 582x500 pixels, ADC – 8 bits.

And up to now the K008 camera is the most miniature in the world among cameras of this class. It was the beginning of creation of third cameras generation.

In all new cameras the image from output of the streak tube is recorded with the aid of professional digital CCD cameras with image input into a computer and its subsequent processing according to the programs that allow to investigators to obtain necessary information quickly and in the most convenient form.

In Fig. 8-11 current camera models of the 3rd generation are presented. In Fig. 8 a third improved model of the K008 camera is shown. This K008Smart camera has almost full control from the PC.

Fig. 8. K008Smart camera: dimensions: 305x85x195 mm, weight: 3.6 kg, power consumption $\leq$20 VA, new compact RU-05R CCD camera – 1392x1032 pixels, ADC – 12 bits.

Frame duration in single-frame mode is from 10 ns up to 10 ms, sweep duration in the streak mode is from 2 ns up to 10 ms, limiting temporal resolution 50 ps.

More than 20 upgrades substantially expanded and improved the camera features in comparison to its predecessor models.

Main features are:

1. Control of all camera modes is done using the computer.
2. Increased thermal and temporal stability of the main parameters.
3. Increased trigger frequency (from 10 Hz to 1 kHz).
4. Adjustable trigger delay of the camera, up to 600 µs, and the ability to trig external devices from the camera with the same advance in time.
5. Built-in optical trigger.
6. Ability to remotely control the camera, including a local area network.
7. Ability to control multiple cameras from one computer.
8. Significantly improved software. In particular, added API (Application Program Interface) for interfacing software of the camera with the software of the consumer and the integration of cameras into their software and hardware.

K010X camera (Fig. 9) with open (pumpable) PV-204XM streak tube is designed for soft X-ray registration (0.1–10 keV). Frame duration in single-frame mode is from 10 ns up to 600 µs, sweep duration in the streak mode is from 2 ns up to 600 µs, limiting temporal resolution 10 ps.

Fig. 9. K010X camera: dimensions: 440x120x205 mm, weight: 5.5 kg, power consumption $\leq$10 VA, RU-05M camera ([5]) – 1392x1032 pixels, ADC – 12 bits.

Fig. 10. Open (pumpable) PV-204XM streak tube, which is used in K010X camera (has one MCP): slit and frame CsJ and Au photocathodes are removable, length 215 mm, width/diameter 75/75 mm, weight 0.75 kg.

K011 camera (Fig. 11) is designed for operation in nine-frame sweep mode with programmable duration of each frame and each inter-frame pause in the range from 50 ns to 500 µs. Maximum framing rate is 10 million frames per second.

Fig. 11. K011 camera: dimensions: 350x120x220 mm, weight: 4 kg, power consumption ≤20 VA, CCD camera RU-05M – 1392x1032 pixels, ADC – 12 bits.

In Fig. 11, two nine-frame sweeps of microwave discharge development in the air at low vacuum are shown on the display: frame duration 0.2 µs, inter-frame pause duration 0.3 µs [6]. Due to the possibility of changing camera sensitivity during the record, it is possible to record processes with brightness intensity varying up to 4 orders.

Famous Agat-SF1 streak camera of second generation is now replaced by K016 camera (Fig. 12) with the same limiting temporal resolution of about 2 ps. Sweep duration in the streak mode is from 0.2 ns up to 60 µs.

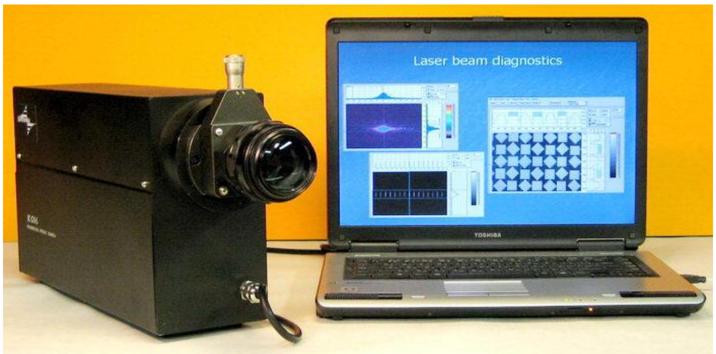

Fig. 12. K016 picosecond streak camera: dimensions: 550x110x220 mm, weight: 6.8 kg, power consumption ≤25 VA, RU-07 CCD camera [5] with fiber-optic input – 1280x1024 pixels, ADC – 12 bits.

Fig. 13. PV-206 streak tube without MCP, which is used in K016 camera: photocathode S1 or S20, length 240 mm, width/diameter 69/48 mm, weight 0.9 kg.

External brightness intensifier with MCP is used in K016 camera. It connects with output of PV-206 streak tube and input of RU-07 CCD camera through fiber optics.

Typical record of femtosecond pulses on the fastest sweep range of the K016 camera is shown in fig. 14.

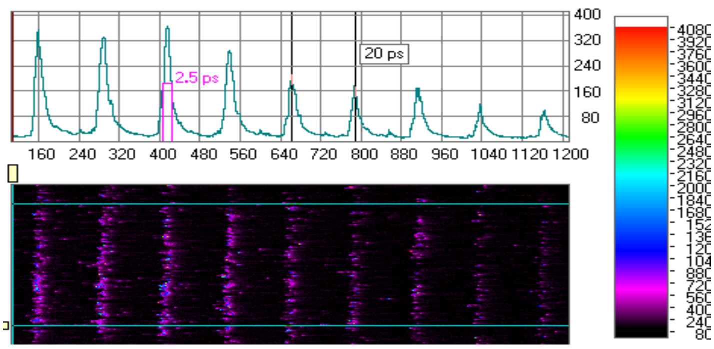

Fig. 14. K016 camera: a series of femtosecond pulses with a period of 20 ps at the output of the Fabry-Perot interferometer at the sweep calibration in the range of 0.1 ns/cm.

All cameras can be controlled remotely via fiber-optic cable with length up to 500 m.

It should be emphasized that camera software allows to display not only the optical pulse sweep image, but also such its characteristics as shape, rise and fall time, duration both at the level of 0.5 from the maximum and at the level of 0.1, which fully corresponds to the requirements of ISO 11554:2006 “Optics and photonics – Lasers and laser-related equipment – Test methods for laser beam power, energy and temporal characteristics” in the part of temporal characteristics measurements (fig. 15).

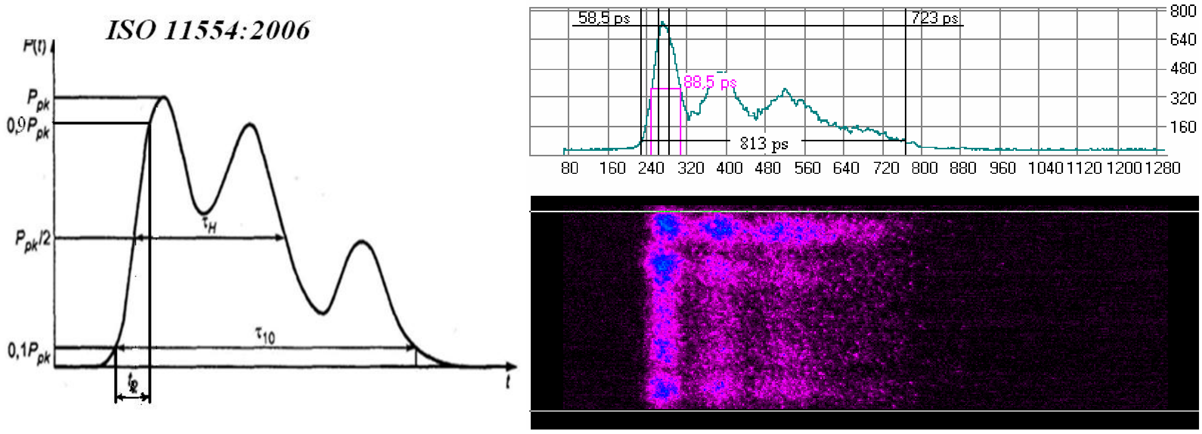

Fig. 15. Left side shows fig. 3 from ISO 11554:2006. Right shows the image sweep pulse of picosecond laser diode, and a pulse shape and time characteristics, in full compliance with the requirements of ISO 11554:2006: rise time – 58.5 ps, fall time –723 ps, half-width – 88.5 ps, duration at 0.1 – 813 ps.

4. CORRECTION OF IMAGE DISTORTIONS

Provided software allows correction of all types of geometric and photometric image distortion in cameras. This substantially increases the reliability of recorded information. Images below show correction efficiency by the example of K008 camera.

4.1. Correction of geometric distortions in the single-frame mode of operation

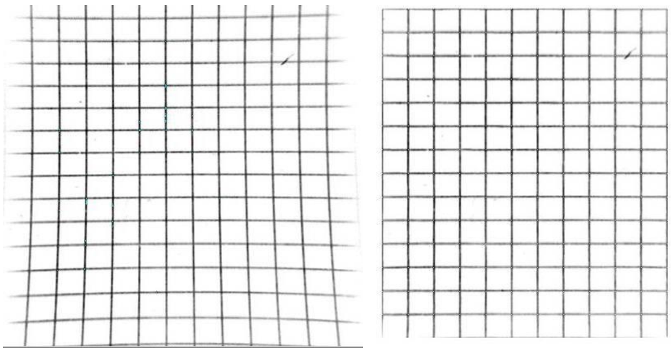

Fig. 16. Image of the orthogonal grid: left - shows a pillow-type distortion by electronic lens of the streak tube, right - shows the same image after correction.

4.2. Correction of geometric distortion and sweep nonlinearity in the streak mode

Geometric distortions can be caused by non-uniformity of streak tube deflecting plates field. They appear in the form of bends of the sweep especially in upper and lower parts of the working field of the screen (Fig. 17 left).

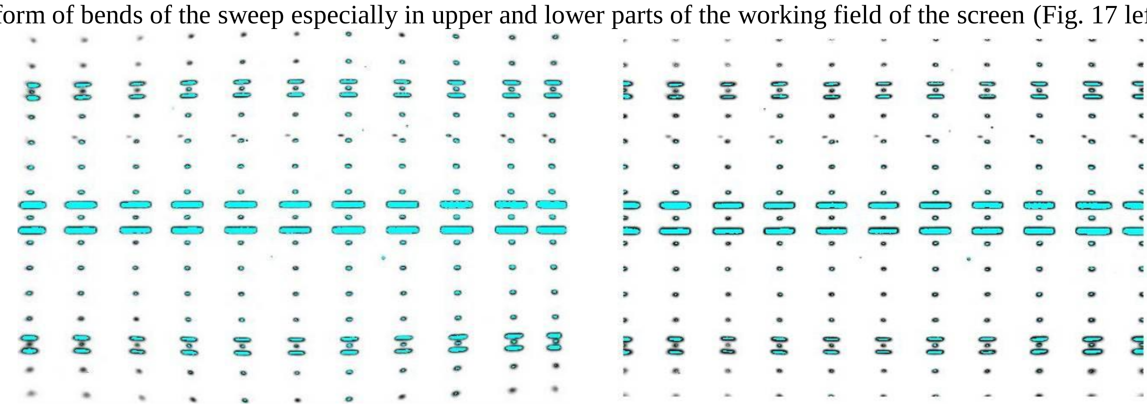

Fig. 17. Sweep image of the test object which is illuminated by series of short equidistant in time pulses at the sweep range of 100 ns/cm: left – image distorted by non-uniformity of the deflecting plates field (one can see the bends of the sweep) and by sweep nonlinearity (15%); right – the same image after correction (the bends of the sweep are absent, the sweep nonlinearity is 3%).

4.3. Correction of photometric distortions

Photometric distortions can be caused by spatial non-uniformity of the photocathode sensitivity, similar non-uniformity of MCP amplification and other factors.

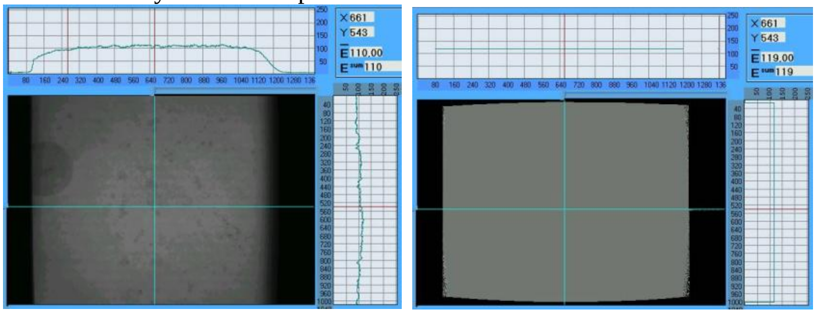

Fig. 18. Images of the uniformly illuminated photocathode field: left – before distortions correction; right– after correction (brightness profiles on axes X and Y became absolutely straight).

5. EXAMPLES OF FAST RUNNING PROCESSES REGISTRATION

5.1. Registration of copper wire electric explosion in the air

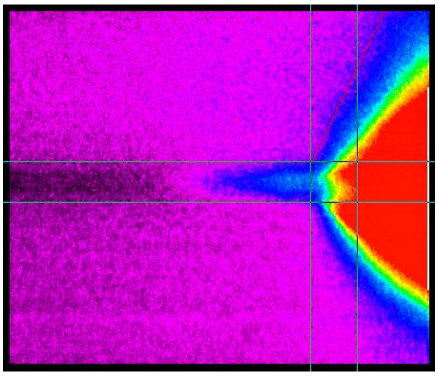

Fig. 19. K008 camera**:** explosion of copper wire with ø 50 µm (streak mode of the camera operation, sweep duration 200 ns, Y-dimension of vision field is 0.8 mm).

Additional illumination from the back side of the wire was used during registration. That is why on the first 1/3 of the sweep length the shadow of the wire is seen. Further comes the own glow of the warming up wire (blue pseudocolor), and after it there is sharply expanding glow of the exploded wire.

5.2. Experiments on needle-free injection (NFI) of drugs into the human body

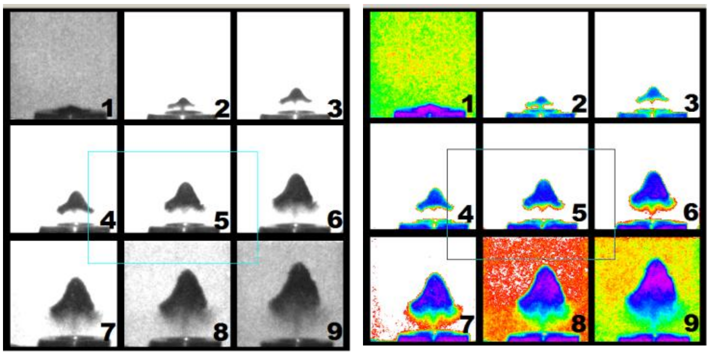

Fig. 20. K011 camera**:** flight of a liquid drop which was lying on a thin metal diaphragm after the diaphragm has been exposed to a shock wave; left – black-white image, right - pseudocolored image. Frames duration 5 µs, inter-frame pauses duration 35 µs, picture field dimensions in the plane of the registered object 8 mm x 8 mm, the average flight speed of a liquid drop ~ 200 m/s.

It should be mentioned that pseudocoloring of half-tone pictures gives an opportunity to see such details, which are almost invisible on black-and-white picture.

CONCLUSION

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