Ultra-high-speed photography

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This article describes several pieces of research devoted to high-speed photography, some of which have been undertaken at the request of the French Atomic Energy Commission and carried out in close collaboration with E. Laviron and C. Delmare, of the Limeil Research Centre, and M. Marilleau, of the Vaujours Research Centre.

High-speed full-image cameras can be grouped into three categories, namely: mechanical, electro-optical and electronic cameras.

Since 1954 mechanical cameras have provided exposure rates of $10^7$ pictures per second, with the possibility of taking a very large number of pictures of the same phenomenon (20 to 100, depending on the version). With these cameras there is a lower limit to the exposure time of about 50 ns.

Electro-optical cameras are composed from an input lens, a shutter consisting of an electro-optic cell — usually a Kerr cell situated between crossed polarizers — and a repeater lens. With these cameras, exposure is obtained by applying a voltage of 15-20 kV across the cell. The exposure time can be reduced to a value of about 1 ns. The chief drawback is that the shutter transmits only 10-20% of the incident light when it is open.

Electronic cameras, which first appeared on the market in 1962, give performances which are superior to those of the cameras already mentioned. They are also suitable for a much wider range of applications. In this article we shall deal only with this type of camera. The heart of the camera in this case is an image-converter tube which acts as a shutter and is used in conjunction with an input objective and a repeater objective.

The image converters which are used in these cameras all consist essentially of a photocathode and a luminescent screen. An image of the scene is produced on the photocathode by the objective lens; the luminescent screen receives the emitted photoelectrons and reproduces the image for a time which is relatively long (0.1 to 10 milliseconds) compared to the time the tube is "open" (e.g. 1 nanosecond).

There are three main types of converter tube:

1) Diode-type converters, consisting of a photocathode and a screen placed in two close parallel planes; we shall describe one version in greater detail below.

2) Triode-type converters, in which operation of the tube is controlled by an electrode in the form of a grid or ring\(^1\).

3) Converters with deflection plates, in which the shutter function is achieved by shifting the electron beam past a diaphragm of very small dimensions\(^2\).

Other types of converter exist which offer possibilities for information storage\(^3\) or charge storage, but they are not yet widely used.

In addition to its function as a shutter an image-converter tube gives a gain in photons and can if necessary be coupled to an image intensifier. This makes it possible for an electronic camera to photograph with very short exposure times phenomena which are not bright enough to be photographed by an electro-optical camera.

As its name indicates, the image converter can also effect conversion of the light frequencies, and it can be sensitive to radiation of different wavelengths, depending on the photocathode used. For example, when the type S 1 photocathode which is sensitive up to 1.1 μm is employed, frequency conversion takes place since the screen which reproduces the image delivers radiation at a wavelength situated in the visible spectrum, centred on 0.55 μm. This conversion makes it possible to use films of very high sensitivity which are practically non-existent for the higher wavelengths.

The lower limit of exposure time provided by these tubes is governed either by the transit times of the photoelectrons between the photocathode and the screen or by propagation phenomena at the surface of the photocathode. These phenomena, which are peculiar to the tube, lead in practice to a lower exposure-time limit of the order of 100 picoseconds.

A converter-tube shutter is opened by applying a high-voltage pulse, usually between 15 and 20 kV, to the electrodes. The width of this pulse approximately


determines the exposure time. If it is desired to obtain exposure times approaching the limiting value allowed by the tube, the control circuits have to deliver pulses whose rise and fall times are of the order of one hundred picoseconds.

The essential characteristics of the tubes and the control circuits are a direct consequence of these requirements. In fact, a voltage variation occurring in such a short time can only be effectively applied to a tube if it is transmitted by a transmission line whose highest operating frequency is of the order of 3 GHz. The tube, of course, has to form an integral part of this transmission line, a circumstance which determines the geometry of the structure on which the sensitive layers have to be formed.

Allowing for the relatively short distance between the photocathode and the screen (cf. formula 1) and for the need to have a useful surface area of several square centimetres, we are obliged to use a transmission line with a characteristic impedance of approximately 25 Ω, and this means that the current will reach a value of about 600 A when a pulse of 15 kV is applied. Therefore, the trigger circuits have to include a high-speed spark gap, and our best results were obtained with a gap of coaxial structure.[465]

We shall see later that the rise time of the leading edge of the wave produced by a circuit comprising a spark gap is proportional to the distance between the electrodes of the gap.[8] A lower limit is imposed on this distance by two factors: a) the useful life, which will be shortened when the gap is reduced, b) the pressure of the gas in the spark-gap cavity. In fact, the operating voltage of the spark gap is determined by the voltage required for the shutter tube, and, if for a given voltage we decide to decrease the distance between the electrodes, we are obliged to increase the pressure (Paschen’s law). Technological problems limit the pressure to twenty or thirty bars, and consequently the distance between the electrodes is made a few tenths of a millimetre.

The final parameters which determine the minimum length of the rise time are therefore the distance between the electrodes of the spark gap and the quality of the various matching elements along the transmission line linking the spark gap to the shutter tube.

Additional requirements concerning the drive circuit come into play if it is desired to obtain a perfectly uniform transmission factor during the exposure and for an accurately defined time. If before and after the actual exposure time the camera has to present the maximum opacity permitted by the converter tube, the waveform of the applied pulse must remain fairly accurately rectangular despite the extremely short duration.

The necessary circuits can now be realized thanks to the progress made at LEP in the field of spark gaps with ultra-high-speed triggering, inserted in coaxial lines. The performance of these spark gaps will be improved still further as a result of research at present in progress.

We now propose to give a brief description of the converter tubes developed at LEP and of several types of camera in which these tubes are used. A description of the tubes has been given by Eschard and Polaert[7] and various equipments have already been described in references[4] and[8]. These equipments were also the subject of a paper read before the Eighth International Congress on High-Speed Photography in 1968[8]. Several examples of spark gaps with two or three electrodes, developed at the Laboratoire Central de l'Armement and LEP have also been described in these articles.

Image-converter tubes

For a number of years now we have been developing a whole family of planar diode shutters[9]. These shutters are very similar in their underlying principle and are based on the technique of activation of photocathodes by the transfer method[10]. On page 235 in this issue a laboratory equipment is shown with which it is possible to make tubes whose useful diameter may be as much as 120 mm. This is important since one of the interesting points about this type of shutter is that it enables the definition of the image to be increased by using increasing diameters.

The main characteristics of these shutters were discussed in a recent paper[11]. We shall first briefly recapitulate the main features to bring out the points which have been the subject of new developments, particularly the possibility of using cathodes which are sensitive up to the near infra-red and constructions suitable for very short exposure times.

Quality of the image

If we place the screen a distance d from the photocathode, the defocusing due to initial velocities results in the following formula for the resolution R (line pairs per mm):

\[ R = \frac{0.6}{d} \sqrt{\frac{V}{\frac{hc}{e} \left( \frac{1}{\lambda} - \frac{1}{\lambda_0} \right)}} \]  

(1)

in which h is Planck’s constant, c the velocity of light, e the electron charge, λ the wavelength of the incident light, λ₀ the wavelength of the transmission threshold of the photocathode, and V the voltage applied at the terminals of the tube (all in SI units).

A resolution of the order of 15 line pairs per millimetre can be obtained when the distance d is sufficiently small. When the useful diameter of the image is as
much as 60 mm, the resolution of the image can be as great as 1000 line pairs per diameter. The absence of distortion is very important, especially when it is required to measure physical characteristics, particle velocities or deformation of materials, or to examine spectra.

Opacity factor

In this range of shutters attenuation of the incident light is due chiefly to a metallic backing on the luminescent screen. The opacity factor depends on the thickness of the metal layer; it is limited by the number and dimensions of micro-fissures in the layer. If the image of a uniformly illuminated surface is examined when the tube is not supplied with power, a series of dots corresponding to faults in the backing will be observed. We have developed a method which allows an opacity factor of over $10^5$ to be attained with a P 11 screen.

Shutter speed

The main factors limiting the shutter speed are the transit time of the photoelectrons, the conductivity of the electrodes, space-charge effects and the manner in which the tube is integrated into the transmission line.

If allowance is made for the shape of the voltage pulse, it can be shown that a transit time of less than 80 picoseconds allows the tube to be used with a minimum exposure time of 100 picoseconds. This is not, therefore, the limiting factor in present tubes but we shall see that it will affect future developments, and the same can be said of the space charge.

The way in which the problem of the conductivity of the electrodes is tackled can be explained as follows. Both the photocathode and the luminescent screen should have sufficient conductivity for the voltage pulse to travel to the centre of the tube without undue deformation. The screens commonly used in this type of tube meet this requirement. The normal photocathodes however are very poor conductors. We have measured surface-resistivity values of $10^8$ ohms per square. A conducting sub-layer must therefore be applied, but this will absorb part of the incident light. For an exposure time of 1 ns the surface resistance of the sub-layer should amount to some dozens of ohms per square. This is obtained at a loss of the order of 50% in gain. For the development of shutter tubes of even higher speed the use of highly conductive and therefore highly absorbing sub-layers will be unavoidable. In this case the light losses may be reduced by applying the conducting layer in an array of very narrow metallic bands, and the types of layer now in use will serve the purpose.

To obtain operating times of less than a nanosecond, we also have had to reconsider the fourth factor, the matching of the tube in the transmission line. In the first generation of shutter tubes, it is inserted in a strip-line terminated with its characteristic impedance. In the model which we are developing at present it is the tube itself which forms the strip-line, and the transition between this strip-line and the coaxial supply cables is inside the tube. Indeed, the presence of a dielectric (glass or ceramic) needed to seal the vacuum tube constitutes a considerable discontinuity which it is difficult to compensate for when one is interested in pulses having leading edges with a width of 0.1 ns. We have now developed vacuum-tight coaxial transitions which can transmit 50 ps pulses without any perceptible distortion. Fig. 1 shows the pulse response measured with a reflectometer.

![Fig. 1. Pulse response of ultra-high-speed shutter type 42-25, measured by reflectometer. Curve 1 input signal, rise time 100 ps. Curve 2 output signal, rise time 120 ps.](image)

To obtain a sensitive zone with sufficient useful width on this tube, we had to use a characteristic impedance of 25 Ω. Transmission is then carried out with two matched coaxial cables with a characteristic impedance of 50 Ω which are joined inside the tube.
**Photocathode**

With the transfer technique mentioned above \[^{10}\] it is possible to produce various types of photocathode, particularly the S 20 and S 24. We recently adapted this technique for the production of tubes with silver-caesium layers (S 1), which are sensitive in the near infrared. *Fig. 2* shows the image of a test pattern obtained with radiation having a wavelength between 1 and 1.2 \(\mu\)m. A resolution of 18 line pairs per mm is obtained.

In view of the increasing interest in experiments using laser beams with wavelengths in this spectral region, shutters equipped with this photocathode may have many applications.

![Fig. 2. Image of test pattern obtained from an S 1 photocathode with radiation having a wavelength between 1 and 1.2 \(\mu\)m.](image)

**Gain**

Tubes developed so far allow us to attain photon gains of 30 at 430 nm.

In the cameras which we have developed, however, the repeater optics use only a small part of the luminous flux emitted by the screen. With tubes of large dimensions it is practically impossible to achieve high relative apertures without introducing troublesome distortion. The use of fibre-optic windows enabled us to resolve this problem. With the type 1325 shutter shown in *fig. 3* an overall gain of the order of 30 can be obtained between the light received by the photocathode and that which falls on the photographic plate.

![Fig. 3. The type 1325 shutter.](image)

In a later phase image intensifiers incorporating channel multipliers will be used. First experiments show that this line of development is very promising.

**Cameras**

We have produced two families of cameras using different types of image-converter tube. Some of these tubes only have one stage, i.e. they consist of a single photocathode and a single screen used in accordance with the principle outlined above. Others comprise two single-stage tubes coupled by a fibre-optic plate inserted between the screen of the first tube and the photocathode of the second; these are called “two-stage tubes”.

The first family consists of cameras whose exposure time is relatively long (5-500 ns). The chief applications for these cameras occur in ballistics and the study of explosives. The second group comprises cameras with extremely short exposure times which are at present in the nanosecond range, and which eventually may be reduced to several hundredths of a picosecond. These cameras are chiefly employed in the field of plasma physics.

**5-500 ns camera with single-stage tube**

A camera from the first family (5-500 ns) is shown in *fig. 4*. It is equipped with a single-stage tube with a diameter of 38 mm or 60 mm. Its main components are the optical head, which contains the shutter tube and has a photographic attachment for polaroid film, and the pulse generator, of very small dimensions, con-
connected to the optical head by two flexible coaxial cables.

The pulse generator delivers a 15 kV pulse of nearly rectangular shape, with a width ranging from 5 to 500 ns and with a rise time of the order of a nanosecond.

The instant of occurrence of the high-speed phenomena to be photographed is usually not very well defined. The exposure has therefore to be triggered by the phenomenon itself. Thus the low values of the trigger delay time (35 ns) and jitter (3 ns) are essential characteristics of the camera.

Fig. 5 shows the circuit diagram of the high-voltage pulse-forming circuit. It comprises a storage capacitor $C$, a switch $I$ and two transmission lines $L_1$ and $L_2$ of unequal length terminated with their characteristic impedance $Z_c$. The shutter tube with photocathode $K$ and screen $S$ is placed between these two lines near their terminal loads. When the switch is closed, a wave-front with an amplitude $V_0$ is transmitted through each line in the direction of the terminal load. The tube thus receives between its two electrodes a pulse $V_s - V_K$ of amplitude $V_0$ whose length is determined by the difference in length $\Delta L$ between the two lines (see right-hand side of fig. 5).

![Fig. 4. Camera with 5-500 ns exposure time. The pulse generator with spark gap is shown on the left, the optical head with shutter tube on the right.](image)

![Fig. 5. Principle of pulse formation for the camera with 5-500 ns exposure time.](image)

Fig. 6 shows a more detailed circuit diagram. The circuit is closed by triggering a 3-electrode spark gap. The trigger circuits comprise essentially a Marx generator built from transistors operating in the avalanche mode and a vacuum-tetrode power amplifier. These introduce a delay of the order of 15 ns.

The basic elements of the pulse-forming circuit are the storage capacitor and the spark gap. The essential feature of the storage capacitor is that it presents extremely low stray inductance of the leads. Its capacitance is 0.1 \( \mu \text{F} \), its stored energy is about 10 joules.
Fig. 6. Block diagram of the camera with 5-500 ns exposure time. The pulse forms at several points are indicated schematically. A more detailed diagram of the output pulse of the voltage divider is shown in the upper left-hand corner.

and its lead inductance does not exceed 2 nH. It is a product of the British firm Hivotronic.

The 3-electrode spark gap is, in fact, a combination of two 2-electrode spark gaps connected in series. Before sparking, the common electrode shows a very high input impedance, equivalent to that of a 2-3 pF capacitor. This arrangement makes it possible to use a vacuum tube for application of the high-voltage pulse. The delay which ionization phenomena would cause in a gas tube is thus eliminated. The time taken to set up the current is more or less proportional to the distance between the electrodes [6]. To ensure that this time is short enough, the distance between the electrodes has to be of the order of several tenths of a millimetre, which means that the gas pressure inside the spark gap has to be raised to approximately 15 bars.

The operation of a spark gap can be divided into two successive stages: ionization and discharge. The ionization time and its jitter depend mainly on what is called the overvoltage (the ratio of the voltage applied between the electrodes to the breakdown voltage). Fig. 7 shows how the ionization time and its jitter change as a function of the overvoltage. During discharge the equivalent circuit of the spark gap consists of an ideal switch in series with an inductance whose value is proportional to the distance between the electrodes. The proportionality constant depends mainly on the intensity of the current through the spark gap; it also

Fig. 7. Variation of the ionization time \( \tau \) and jitter \( \Delta \tau \) as a function of the "overvoltage" (voltage \( V \) applied to the electrodes divided by breakdown voltage \( V_b \)).
depends, but to a lesser degree, on the nature of the gas and the shape and nature of the electrodes, and it is practically independent of the pressure. For a current of approximately 500 A, the proportionality constant is of the order of 45 nH/mm.

We have studied the effect of a certain number of parameters, particularly the distance between the electrodes, on the service life of high-speed spark gaps. It depends, but to a lesser degree, on the nature of the gas and the shape and nature of the electrodes, and it is practically independent of the pressure. For a current of approximately 500 A, the proportionality constant is of the order of 45 nH/mm.

We have studied the effect of a certain number of parameters, particularly the distance between the electrodes, on the service life of high-speed spark gaps. It

was found that the further the electrodes are apart the longer the life of the spark gap is. The choice of the electrode spacing is therefore a compromise between operating life and a low rise time. Thus, in the case of the camera with which we are concerned here, an electrode spacing of 0.3-0.4 mm gives a rise time shorter than 1.5 ns and operation is still satisfactory after 30 000 discharges.

The main characteristics of this camera are the following. The high-voltage pulse applied to the shutter tube has an amplitude of 10-15 kV, a width of 5-500 ns, a rise time of 1.5 ns and a fall time of 10% of the pulse width. The trigger delay time is 35 ns, with a jitter of 3 ns. The maximum repetition rate is one pulse per minute.

A camera with a performance similar to that described here is being developed by SODERN (see page 214). It will have a sealed spark gap, which makes it easier to operate.

Test facilities for exposure times between 5 and 500 ns

We have built two test facilities (which in fact constitute a kind of experimental cameras) to aid the development of electronic shutters; one for use with single-stage 120 mm diameter tubes and the other for use with two-stage tubes. The circuits are of the same type as those described above.

Fig. 8 is a photograph of the test camera for tubes with a diameter of 120 mm. The amplitude of the high-voltage pulse is adjustable between 8 and 30 kV. The difficulties which had to be overcome to obtain a short exposure time are: 1) the capacitance presented by the tube, which is roughly 100 picofarads; and 2) the impedance mismatch caused by the presence of such a large tube in a strip transmission line which otherwise is connected to coaxial cables. We had decided to use strip-line about 230 mm wide. Because of the weight of the tube it is difficult to incorporate its supports in this line. On the other hand, this line should form the extension of an RG 214 U 50-Ω cable whose dielectric has an external diameter of 7.2 mm. The transition from this cable to the strip-line is dif-
difficult to achieve with good matching of the characteristic impedance and a sufficient dielectric strength to withstand 30 kV. Despite these difficulties the exposure time is still less than 10 nanoseconds. The performance in other respects is identical to that of the camera described above.

Fig. 9 is a photograph of the test camera for two-stage tubes. This system comprises two generators...
housed in a single box but independently controlled, one for the first stage and the other for the second stage of the tube under test. The generator for the first stage is identical to that used in the camera already described, but incorporates facilities for adjusting the voltage applied to the tube between 8 and 15 kV. The high-voltage pulse applied to the second stage should be rather wide because of the persistence of the luminescent screen of the first stage. The width of this pulse can be varied between 1 and 100 μs, and its amplitude between 8 and 15 kV.

Camera with exposure time of 1-2 ns

We shall now describe an apparatus belonging to the second family of cameras, allowing extremely short exposure times. The minimum exposure time is at present 1 ns. This should be reduced in the near future to 0.3 ns.

A camera of this type is again made up of two essential parts: the optical head, with the image-converter tube, and the high-voltage pulse generator (fig. 10). The converter tube, with which the input optics, the repeating optics and the photographic attachment are associated, can be seen at the top. A reflex viewfinder is used for focusing the image on the photocathode. The lower part contains the electronic control circuits. These consist mainly of a pulse amplifier and a high-voltage pulse-forming circuit which delivers a single pulse with an amplitude of 12 kV and a half-height width of 1 or 2 ns each time it is triggered. The pulse-forming line is contained in the removable horizontal cylinder.

To photograph a single random luminous phenomenon, such as a break-down in the air caused by the focusing of a laser beam operating in the triggered mode for example, the camera can be operated by a low-level pulse of about 6-10 V taken from a photocell receiving part of the laser beam. The image of the luminous phenomenon has then to be stored in an optical delay line for a time which is at least equal to the trigger delay time of the camera. In our case the optical delay lines used have delay times of approximately 35 ns. It is therefore absolutely essential that the 12 kV pulse which causes the tube to open should be applied to the tube with a delay of less than 35 ns.

Another essential characteristic of the camera is the jitter in this delay. To analyse a luminous phenomenon it is necessary to be able to shift, in steps of, say, 1 nano-

![Diagram](image-url)

Fig. 11. Block diagram of camera with 1-2 ns exposure time. A diagram of the output pulse of the voltage divider is shown in the upper left-hand corner.
in the avalanche mode. The main features of this circuit are its high sensitivity, its very short delay (less than 5 ns) and negligible jitter (0.2 ns). The amplitude of the pulse delivered readily attains 1 kV with a rise time of 2 ns. The difficulty is in coupling the generator to the vacuum tube which follows it, because the input impedance of this tube is that of a capacitor of about 50 pF, which, for a rise time of 2 ns, means currents of approximately 20 A. This is a value which is difficult to achieve with semiconductors, and a balance has to be struck between the rise time of the output pulse and the reliability of operation. Our circuit has a rise time of approximately 5 ns due to a series resistor inserted at the output of the Marx generator.

2) A power amplifier using a vacuum tube type 4 PR 60 B. This delivers the required output pulse of 15 kV at the required power (15 A for a rise time of 5 ns across a 5 pF capacitor). The input drive required for this output is 1 kV at the grid. A gas tube (e.g. a hot or cold-cathode thyratron) would also give this performance but the vacuum tube has the advantage that it introduces a delay of less than 10 ns, practically without jitter, whereas a gas tube would have a delay of 100-200 ns and cause a jitter of 20-50 ns.

3) A 3-electrode spark gap inserted in a coaxial arrangement consisting of an open-circuit pulse-forming line with an electrical length of 1 or 2 ns at one end, and a transmission line at the other, the latter being linked by a very carefully matched transition to a strip-line providing connection to the 'shutter tube. The characteristic impedance of the device is 25 ohms. The d.c. voltage to which the pulse-forming line is charged may be as high as 30 kV (for a 15 kV pulse applied to the tube). The spark gap is pressurized with high-purity nitrogen at a pressure of 40-50 bars.

As already explained, a distance of the order of one tenth of a millimetre has to be maintained between the electrodes to obtain the 300-400 ps rise time required for an exposure time as low as 1 ns. This meant that considerable difficulties had to be overcome to ensure a suitable mechanical strength at 50 bars pressure without preventing a rapid change of the exposure time; a dielectric strength to withstand 300 kV d.c.; a negligible mismatch; sufficient reproducibility of spark-gap adjustments after each change in exposure time; sufficiently long service life, despite the spark erosion and the spacing of the order of 1/10 mm between the electrodes; and finally the exclusion of spontaneous or untimely triggering.

By submitting the effect of each of the parameters of the pulse-forming circuit to extremely detailed analysis we were able to give the system optimum characteristics for each of the above requirements, and at the cost of extremely stringent mechanical tolerances, strict inspection of surface conditions, and far-reaching technological precautions during assembly we have succeeded in ensuring satisfactory reproducibility and reliability. The performance obtained can be summarized as follows:

a) Overall trigger delay time of less than 30 ns.

b) Jitter of less than 3 ns.

c) Spontaneous triggering occurrence of less than 2%.

Incidentally, complete suppression of unwanted triggering has been achieved with a system of automatic cut-out of the extra-high voltage; with this system the camera has to be "set" in advance, one second before it is used.

d) Service life exceeding 50 000 discharges.

e) Rise and fall time of approximately 350 ps.

f) Spurious signal amplitudes measured on the tube of less than 10% of the pulse amplitude.

The electrical pulse applied to the tube is measured by a capacitive divider inserted in the transmission strip-line near the tube. This divider introduces an initial attenuation of 54 dB, with an inherent rise time of 0.2 ns. The difficulty was to obtain this performance while giving the divider a "time constant" (the period during which it introduces dynamic errors of less than 5%) of approximately 5 ns.

Fig. 12 shows the transition between the pulse-forming coaxial line and the strip-line and also how the tube is inserted in the latter.

To sum up, we may say that the principal feature of the cameras which we have just described is that they permit full-image exposures with the following characteristics: very short exposure times, e.g. 1 ns; an extremely wide range of exposure time, e.g. 1-500 ns; a very low trigger delay time and jitter (30 and 3 ns, respectively); a very substantial light gain; and an almost total absence of distortion.

This last feature in particular opens up prospects for many interesting applications such as three-colour printing, photo-feedback and relief photography. All these processes involve the superimposition of several images and thus require an almost complete absence of distortion.

Improvement of the cameras is possible in a number of directions, such as the development of luminance intensifiers using channel multipliers giving a considerably higher light gain; the development of new super-high-speed tubes characterized chiefly by the fact that the sensitive layers (photocathode and screen) are integrated into a strip transmission line, which will

allow the exposure time to be reduced to approximately 300 ps; the development of new types of triggered spark gaps whose essential characteristic will be that they have a jitter as low as 300 ps; the miniaturization of the optical head, enabling several shutter tubes to be grouped together within a small space, so that full-image exposures of several successive stages of the same phenomenon can be made.

Summary. After briefly reviewing the various types of camera which can be used for ultra-high-speed photography, the authors describe several image-converter shutter tubes and various cameras developed and produced at LEP. The shutter tubes are of the planar-diode type. By making use of a fibre-optic plate they can be connected in cascade to form a two-stage tube or combined with channel multipliers for a much higher light gain. They may have a diameter of 38 mm, 60 mm or 120 mm.

The cameras developed can be grouped into two main “families”: a) Cameras with exposure times of 5-500 ns; a brief description is given of a single-stage tube version with a diameter of 38 mm, a two-stage version with a diameter of 35 mm and a single-stage version with a diameter of 120 mm. b) Cameras with exposure times of the order of 1 ns. Two versions have been made, with exposure times of 1 ns and 2 ns, using a single-stage tube and a diameter of 38 mm. Development still in progress should result in a camera with an exposure time of 300 ps. All these cameras are actuated by an electrical pulse with an amplitude of several volts. The trigger delay is 35 ns and the jitter, at present 3 ns, will be reduced to about 300 ps as a result of progress made in the field of ultra-high-speed spark gaps. The principal features of these cameras are their light gain and the absence of distortion on one hand and the extensive exposure range and the low delay and jitter values on the other.