A HIGH SPEED PHOTOGRAPHIC SHUTTER BASED ON THE KERR-CELL PRINCIPLE

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A new single frame Kerr-cell shutter is described. Its electrical system is based on the principle of a four pulse timer driving a high voltage square pulse generator. A sequence of pulses: scope driving, synchronizing, shutter opening and closing, is continuously adjustable and covers the region from 0.1 μsec to a few hundred μsecs. The shutter may by positioned either in front of a spectrograph or furnished with a telephoto lens and used as a camera for photographing self luminous events. The shutter is efficient within the spectral range from 450 nm up to 770 nm. A nitrobenzene purification procedure is also described.

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Introduction

There are very many interesting problems in the field of plasma physics and electric discharge study where a photographic shutter with a few μsecs exposure time and a delay unit covering the region up to several hundreds of μsecs, both adjustable, are necessary.

None of the existing developments of ultra-high speed cameras [1–2] is furnished with timing equipment of this type, covering such a broad region of exposures and delays.

Müller's shutter [1] is the closest approach to the demand of continuity of adjustment. This design incorporates a delay unit composed of a set of ten sub-units, each of them being, in principle, a segment of delay cable of fixed length. The adjustment of delays is then stepwise. The exposure time is also adjusted by the same method. Müller's shutter is not capable of covering the region of tens and hundreds of microseconds because of the enormous lengths of cables involved.

The same conclusion is valid for the Kerr-cell shutter developed by Früngel *et al.* [2] and built into a motion picture high speed camera.

Apparatus

The apparatus described was preliminarily announced in Ref. [4] p. 94, and in Ref. [5].

1. Electric system

The problem of obtaining a short exposure time with the Kerr-cell resolves itself into one of rapidly charging and discharging the interelectrode capacitance of the cell. In this

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shutter the capacitance amounts to 60 pF. The electric equipment of the shutter is based on the circuit shown in Fig. 1.

Initially the two plates of the cell K are at the same potential (ground potential), whereas the condenser C is charged to a potential[1] approx. 10% higher than $U_{\max}$ *i. e.* the potential of the fully opened Kerr-cell.

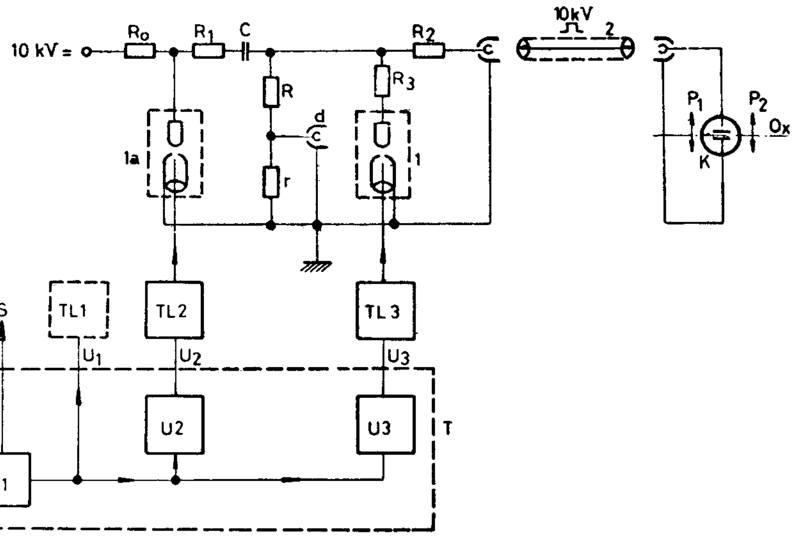

Fig. 1. The electric circuit of the shutter, K — Kerr-cell, P_1, P_2 — polarizers, B — button press, G — calibration generator input, T — timer, $U1$, $U2$, $U3$ — univibrators, U_1 — starting signal output, S — synchroscope trigger signal, $TL1$, $TL2$, $TL3$ — pulse units of the ignition spark voltage (a thyratron circuit with inductive load), $r = 510\,\Omega$, $R \sim 100\,k\Omega$, C — condenser $0.1\,\mu$F, $R_0 = 10\,M\Omega$, R_1, R_2, R_3 — damping resistors $10 \times 10\,\Omega$, $200\,\Omega$, $2.5\,\Omega$, respectively, Ox — Kerr-cell optical axis, 1*a*, 1*b* — trigatrons, *2* — coaxial cable of $75\,\Omega$ impedance, d — voltage divider output

Polarizers are in the crossed position, *i. e.*, their polarization planes are perpendicular according to the scheme: $P_1 \perp P_2$ (see Fig. 1). Otherwise, initially the shutter is optically closed.

The triggering procedure is started by button press B. (In routine use, when, *e. g.* a precise calibration of the timer is necessary, alternatively a sequence of -40 V pulses from a standard generator may be fed into the extra input G).

1.1. The timer T

The timer T (Fig. 1) is composed of three component univibrators $U1$, $U2$, $U3$. (For their detailed description see [6]). They deliver a sequence of four pulses: at an instant of time t_0 — a synchroscope trigger signal marked S, at instant t_1 a starting signal U_1

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[1] For a detailed definition of $U_{\max}$ and a description of the $U_{\max}$ dynamic method of measurement see Refs [11] and [8-10].

triggering the physical event being photographed (t_1 may be arbitrarily chosen either coinciding with t_0 or $t_1 = t_0 + 1$ μsec). The $U2$ and $U3$ units form a gating system for the Kerr-cell: the former generates an opening signal U_2 for the Kerr-cell at an instant t_2 and the latter generates a closing signal U_3 at an instant t_3.

The duration of the time delay of opening t_2-t_1 may be adjusted within the range 2.3—22.5 μsec, and that in closing the Kerr-cell t_3-t_1 within 3.3—390 μsec, respectively. Thus the exposure time t_3-t_2 may be varied from approx. 390 μsec down to 0.1 μsec (see Results).

1.2. Ignition spark units (*TL* units)

According to the scheme in Fig. 1, the timer pulse generated by any of its univibrators U, is fed into one of the three identical *TL* units. A *TL* unit is mainly a high voltage generator (composed of a thyratron circuit with inductive load) initiating the central electrode c in the trigatron *1* (Fig. 2) and thus triggering the Kerr-cell circuit. The univibrator pulse fed into the thyratron grid through a chain of semiconductor diodes d (Fig. 2) releases the thyratron T. A ferrite core pulse transformer L, transforming ratio 1 : 4) is an inductive load for the thyratron secondary circuit. The inductance of the primary transformer windings amounts, to 1.5 μH and that of the secondary to 16.5 μH. The inductance and capacity combinations L_1C_3, L_2C_4 and diode chain d play the role of a filter decoupling the thyratron grid and heater circuits joined through the voltage supply.

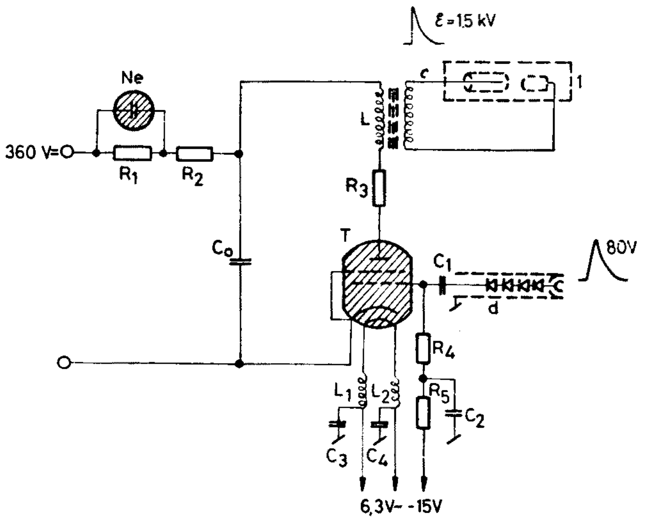

Fig. 2. Ignition spark units (*TL* units). *1* — trigatron (three electrode air spark gap switch), c — trigatron central electrode, d — semiconductor diode (D2E type) chain, T — thyratron 20 A 2 type, L — ferrite core pulse transformer, *Ne* — neon signal lamp, $R_1 = 150\,k\Omega$, $R_2 = 200\,k\Omega$ $R_3 = 1 \div 5\Omega$, $R_4 = 20\ k\Omega$, $R_5 = 50\,k\Omega$, $C_0 = 0.5\,\mu$F, $C_1 = 10$ nF, $C_2 = 2\,\mu$F, $C_3 = C_4 = 0.1\,\mu$F, $L_1 = L_2 = 10\,\mu$H, $\mathcal{E} = TL$ transformer electromotive force

Results

2.1. Shutter action

A typical result of light beam shuttering action is illustrated in Fig. 3, where the shutter transmission T *vs.* time is given[2]. The picture reproduces a rectangular shape without any great distortion.

2.2. Minimal exposure time

The authors have adopted the following arbitrary criterion of the minimal exposure time: The shuttered light beam exposure time is to be continuously shortened until amplitude decrease becomes evident. Thus the rectangular shape of Fig. 3 converts into the triangular[3] one of Fig. 4.

Again the triangle height in Fig. 4 is equal to the height of the rectangle in Fig. 3. The half-width of the pulse of Fig. 4 is adopted as the minimal exposure time. This amounts to 0.1 μsec. Fig. 4 is a superposition of ten single oscillograms (time separation between two succesive oscillograms is 15 secs). A narrow vertical line at the peak proves that there is no jitter in the electronic system at that particular time scale.

Pulse rise time equals 0.10 μsec and decrease time equals 0.09 μsec (both defined as the pulse duration between 0 and 100% amplitude).

These figures are the same as those of the best shutters involving standard vacuum-valve electronics in the circuitry [1] and of Walker p. 96 in [7]. Further improvement may be achieved by using wave guide techniques [2].

2.3. Timing action

Fig. 5 is a superposition of synchroscope traces of six signals. A reference rectangular light signal (as shuttered by the Kerr-cells) should be compared with the set of four signals generated by the timer unit and with the time base. In the group of four lower traces there

TABLE I

Timer signal characteristics

Signal	Explanation footnote no	Pulse amplitude [V]	Pulse rise time[4] [μsec]	Pulse half-width [μsec]	Jitter[5] J [nsec]
S		−14	0.3	1.8	0 by definition
U_1	1	$30 \div 47$	0.5	2	
U_2, U_3	2	80	0.35	1.2	$\leqslant 10/60\text{x}$
U_2, U_3	3	55	0.35	0.8	

[1] signal of the U1 output loaded by the synchroscope only,

[2] unloaded output,

[3] loaded by the thyratron grid impedance in the *TL* unit; thyratron anode voltage off,

[4] defined as the pulse duration between 10% and 90% of the amplitude value,

[5] the total spread in the indicated number of scope traces is taken as the jitter J. The spread is measured as the interval of time between the pulse under consideration and the signal S.

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[2] Transmission T is measured by the scope deflection (a photomultiplier signal) proportional to the light intensity transmitted by the shutter.

[3] A triangle is obviously formed because of the finite rise time of the electrical pulse driving the Kerr-cells.

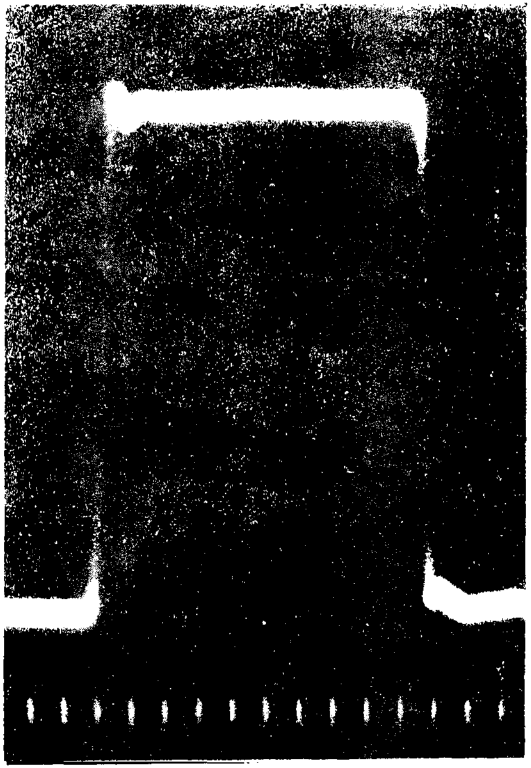

Fig. 3. Time variation of the transmission T of the shutter under typical operational conditions: Exposure time 2 μsec. Time base 0.2 μusec/div

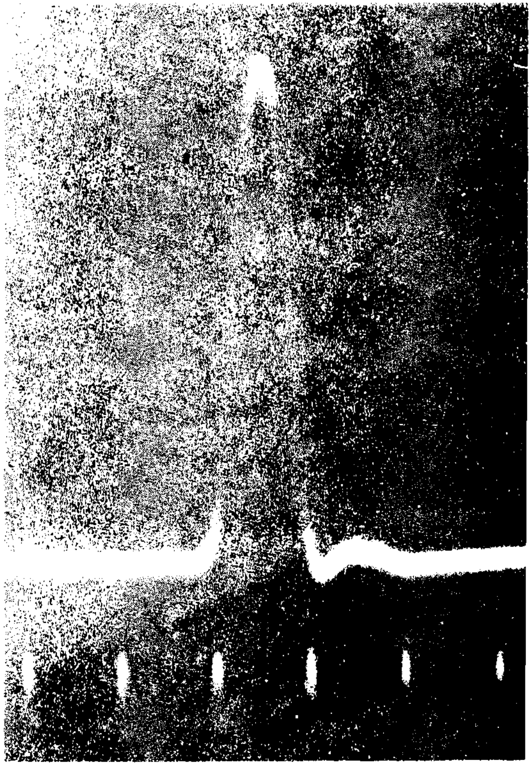

Fig. 4. The minimal exposure time 0.1 μsec. Time base 0.2 μsec/div

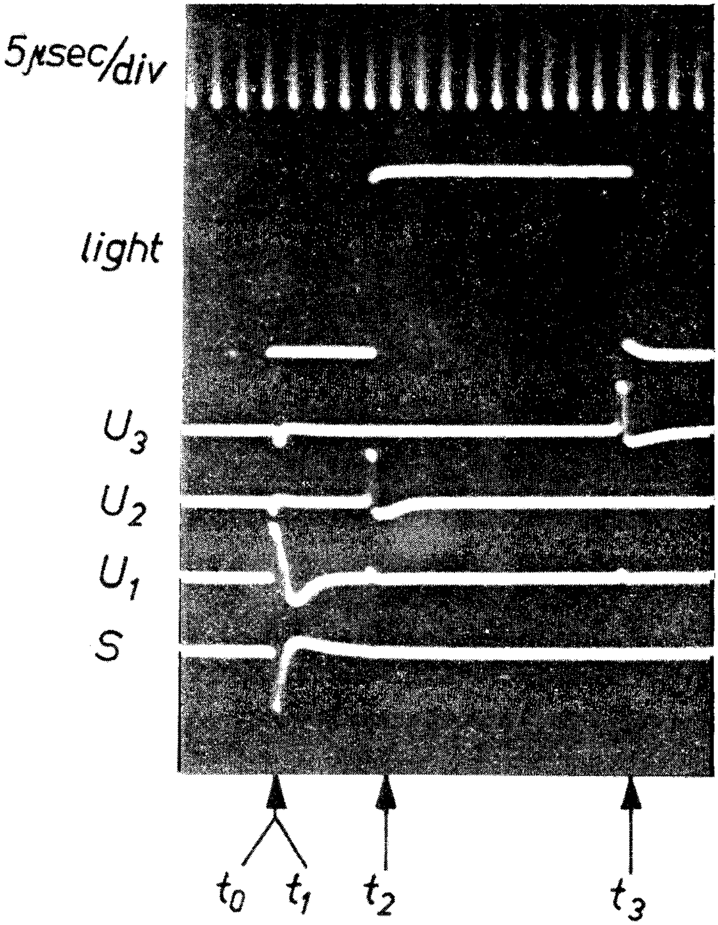

Fig. 5. Timing action — a superposition of six timer signals; starting from the bottom: synchroscope trigger signal marked S, physical event trigger signal marked U_1, Kerr-cell opening U_2 and closing U_3 signals, reference rectangular light signal as shuttered by the Kerr-cell, time base 5 μ sec/div

exists on each of them an extra signal of minute amplitude (negatively polarized) corresponding to stray capacitance coupling between U_2, U_3 signals and S, at an instant t_0 or t_1. Correspondingly, on the last two traces (U_1 and S) there is a pair of similiarly generated, minute amplitude signals (positively and negatively polarized, respectively). They correspond to the t_2 and t_3 instants of time. Because of their small amplitude values they neither actuate the *TL* units nor relaese the scopes time base; nevertheless they play a very useful role in the problem of time axes synchronization.

The four lower traces in Fig. 5 are amplitude normalized to the same height. The actual voltage is given on the left hand side of Table I.

2.4. Operational results of the *TL* units

The electromotive force $\mathcal{E}$ high voltage pulse rise time is quite steep (Table II). The jitter[4] is caused by the electronic system itself with the exclusion of the trigatron.

TABLE II

The *TL* unit characteristics

Signal	Pulse amplitude [V]	Pulse rise time [μsec]	Pulse half-width [μsec]	Jitter J [nsec]
$\mathcal{E}$	1200	0.13	0.2	7/20 x
	or 2000	0.15	0.5	10/60 x

The thyratron jitter is measured on the thyratron grid and equals 20 nsec/20x. When the trigatron *1* (Fig. 2) is connected to the *TL* output the trigatron ignition spark jitter is increased to the value of 40 nsec/60x.

3. *Spectral characteristics of the shutter*

The measurements of the spectral transmission of the Kerr-cell and of the polarizers were performed on Beckman and Hilger spectrometers, respectively. The results are given in Figs 6–8.

In Fig. 6 there is a sharp cut-off of the Kerr-cell transmission at the 420 nm wavelength caused by absorption in nitrobenzene.

The transmission of the two polarizers (Bernotar type, manufactured by Zeiss, Jena) is given in Fig. 7 separately for each of them, whereas in Fig. 8 the polarizers polarization planes are aligned alternatively in parallel or perpendicularly ("crossed").

3.1. Spectral region of the shutter

Comparing Figs 6–8, the following conclusion can be drawn: The shutter is efficient within the wavelength range from 450 nm up to 770 nm. The short wave limit is superimposed by the joint action of the polarizers and nitrobenzene absorption, and the long wave

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[4] See the definition in footnote 5 of Table I.

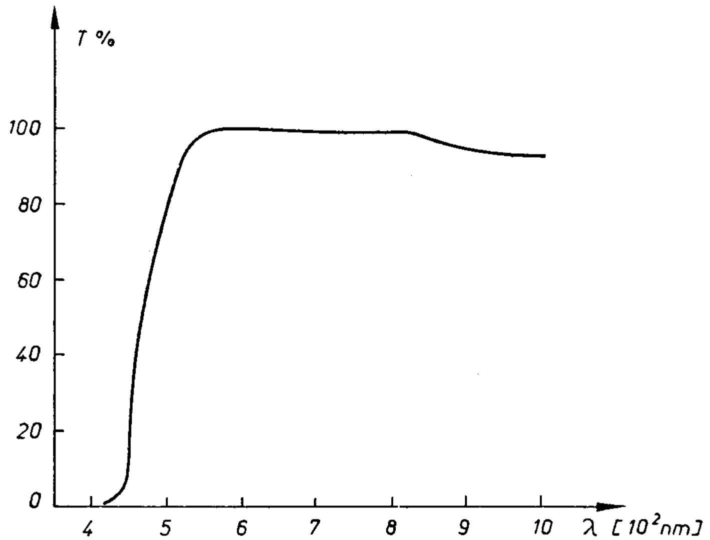

Fig. 6. Spectral transmission of the Kerr-cell (nitrobenzene filled in, no polarizers)

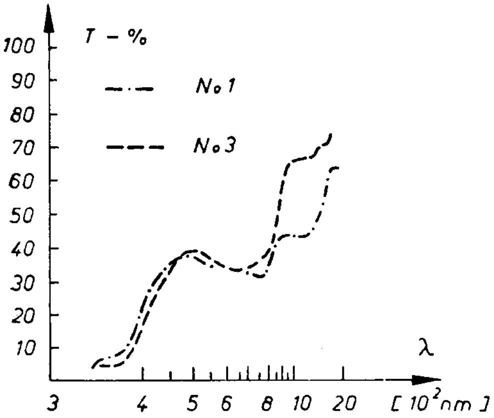

Fig. 7

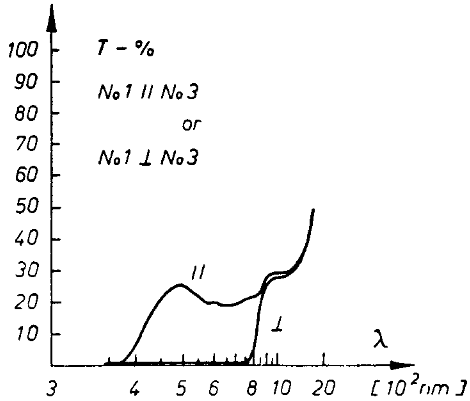

Fig. 8

Fig. 7. Spectral transmission of the two Bernotar polarizers

Fig. 8. Spectral transmission of the optically aligned pair of Bernotar polarizers (polarization planes parallel ∥ or perpendicular ⊥)

limit by inefficiency of the Bernotar type polarizers in near infra-red (they are transparent there in the crossed position).

3.2. "Closed to open" polarizer ratio

It should be borne in mind that for a monochromatic light beam two factors are important in any measurements of "closed to open" ratio, *i.e.*, in measurements of shuttering efficiency: spectral composition of the light beam and spectral sensitivity of the detector applied[5].

The following figures were obtained by the authors: 1 : 300 when an M 12 QS type photomultiplier (manufactured by Zeiss, Jena) and no filter was used, and 1 : 1000 with a Schott — Jena VG 10 filter, which proves that this factor may vary within a quite considerable range according to the spectral characteristics of both the light shuttered and the detector.

3.3. Transmission of the shutter

In order to have an idea of the transparency of the shutter in the "open" phase of its shuttering process, the transmission was measured at the point of rather poor transparency of the polarizers, *i.e.*, at approx. 646 nm, and the value of 20% was obtained.

3.4. Nitrobenzene purity problem

In routine use there is a need of static characteristics measurements of the Kerr-cell, *i. e.* measurements of the transmission *vs* DC high voltage. Under these circumstances high purity nitrobenzene filling of the cell is required.

There are three important factors affecting the performance of a Kerr-cell and concerned with the purity of nitrobenzene: the preliminary current flow effect and resulting rate of Kerr-cell heating and the rate of deterioration of a nitrobenzene sample.

It is a well-known fact [11] that there is a preliminary current flow when the Kerr-cell is switched on. Initially nitrobenezene specific resistance ϱ_0 is low and after a certain build-up time t_b it reaches its maximum value $\varrho_{\max}$. It is evident that we should minimize build-up time because of Kerr-cell heating and the heavy electrical load it represents for the high voltage supply.

When the Kerr-cell is continuously operated (*i. e.* without switching off the driving voltage), $\varrho_{\max}$ remains constant. However, when it is switched off a nitrobenzene sample gradually deteriorates and after a certain time, t_d, specific decreases resistance to its initial value ϱ_0. A deteriorated sample needs an extra preliminary current flow in order to restore its proper working conditions.

This phenomenon obviously represents a nuisance from the operational point of view and puts a certain limit for the maximum allowed time interval between two subsequent signals when the Kerr-cell is driven by an interrupted sequence of signals. This time interval should not be longer than t_d.

The authors have applied a multistage procedure of nitrobenzene purification, including the electrical method.

Commercially obtained, "pro analysi" purity nitrobenzene (manufactured by FOCH Gliwice Ltd., Poland) should be distilled three times in the usual way under pressure lowered to a few torr, after which the electrical method of purification should be applied.

We came to the conclusion that in order to obtain the best value of $\varrho_{\max}$ we make use of the preliminary current phenomenon itself. This stage of purification is carried out in

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[5] No particular attention was paid to this fact by Müller [1], whose estimation of the „closed to open" ratio 1 : 10^2 suggests too broad a spectral region of the light beam not matching the polarizers.

a separate glass vessel with its own electrode system shaped similarly to the Kerr-cell itself. After 30 minutes direct current flow under 20 kV potential difference we obtain the best nitrobenzene sample *D* (see Table III). Specific resistance measurements should be done below 15 kV potential difference in order to avoid high potential leakage currents on the external walls of the glass vessel. (The higher the voltage the more prominent the leakage.) When the sample *D* is poured into a Kerr-cell, carefully washed in advance, preliminary current flow treatment lasts only a few seconds. Further improvement can easily be seen when the deterioration process is taken into account: the electrically purified nitrobenzene will last for several months.

TABLE III

Results of electrical purification method

Sample	$\varrho_{\max}$ (MΩm)	t_b	$\varrho_{\max}/\varrho_0$	t_d
Nitrobenzene				
A = Commercial, *p. a.* purity	$2\div3\times10$:	15 min	—	20 min
B = distilled twice	12	5 min	—	20 min
C = distilled three times	32	3 min	—	20 min
D = *C* after 30 min d. c. flow	100	1 sec	50	several months
E = *D* poured into the Kerr-cell	3	10 sec	20	several months
F = *D* after resistance build-up	24	1 sec	20	several months
Acetone, *p. a.* purity	1.5	4 min	75	—
Benzene, *p. a.* purity	$>4\times10^4$	<1 sec	≈1	—

Special care should be taken in the choice of suitable organic solvents in terms of their specific resistance. The two last stages of cleaning by means of organic solvents should be carried out using acetone of *p. a.* purity and later, after drying of the walls, *p.a.* benzene should be applied. Cleaning the external walls by means of *p.a.* benzene also greatly aids in prevention of current leakage. Both the above-mentioned solvents were electrically purified as well, for small, inevitable remnants of them in the Kerr-cell might influence its resistance. The resulting purity of the solvents is listed in the last two lines of Table III.

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