Crowbar System in Isar I

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IPP 4/59 June 1968

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Die nachstehende Arbeit wurde im Rahmen des Vertrages zwischen dem Institut für Plasmaphysik GmbH und der Europäischen Atomgemeinschaft über die Zusammenarbeit auf dem Gebiete der Plasmaphysik durchgeführt.

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Abstract

The 2.7 MJ capacitor bank ISAR I was already described in the reports IPP 4/12 - 1964 and IPP 4/26 - 1966. In the meantime a passive crowbar system has been added. The arrangement of the crowbar system is described in this report. Special care went into the conception of a trigger system consisting of a "swinging trigatron", master spark gap and 18 two-stage Marx generators. Further are described precautions against prefiring of the crowbar spark gaps and the loading of a crowbar spark gap due to prefiring.

Contents:

Crowbar System in Isar I

1. The 2.7 MJ bank Isar I

The Isar I device can produce a magnetic field of 170 kG in a short time (approx. 10 /usec). The bank consists of 252o single capacitors which can store an energy of 2.7 MJ at a maximum charging voltage of 40 kV and can be discharged to a single-turn (theta pinch) load coil across 252 spark gaps. The stored energy is thereby converted to magnetic energy (B = 170 kG; $\dot{B}_{t=0} = 2.6 \cdot 10^7$ kG/sec) in 10 /usec. The bank is described in detail in (L 1), (L2), and (L 3). The bank, which comprises 252 groups of capacitors connected in parallel to the load coil, is shown in Fig. 1. One such group is shown schematically in Fig. 2.

2. Modes of operation

2.1 Oscillating discharge

When the start spark gaps are triggered, this produces an oscillating discharge in the form of a subcritically damped sinusoidal oscillation. The parameters R, L, and C governing this oscillation are given in the equivalent circuit diagram of the bank in Fig. 3. These values result in the current-voltage characteristic shown in Fig. 4a. With this mode of operation the plasma confinement time is governed by the duration of a half-cycle of the discharge, this being about 20 /used.

2.2 Crowbar discharge

In order to achieve a longer confinement time, the already installed bank was provided subsequently with a crowbar system. This serves to short-circuit the capacitors at the time of the current maximum. At this instant the energy of the circuit is mainly in the magnetic field of the load coil.
In a crowbar discharge, the dynamic phase up to the current maximum (see Fig. 4a; $t < t_1$) is subject to the same operating conditions as in oscillating operation. For times $t > t_1$ the current is com-

posed of an exponentially decaying fundamental amplitude and a spurious amplitude of the form cos $\omega t \cdot e^{-\delta t}$ (see Fig. 4b). The spurious amplitude occurs because the storage and load circuits are not completely decoupled owing to the inductance present in the crowbar branch. The currents, voltages, and magnetic pressure in the load coil are given in graph form in Fig. 4. At a charging voltage of 40 kV and a discharge frequency of 25 kHz, a maximum current of 20 MA is obtained. In a crowbar discharge, one obtains a $\frac{L}{R}$ time constant of 105 μsec and a ripple of 8 %.

2.3 Approximate calculation of the electrical parameters

The time variation of the currents in the individual branches and of the voltage at the capacitor in a crowbar discharge can be found from the equivalent circuit diagram in Fig. 5a.
A crowbar system can be calculated approximately by means of the following relations, ohmic resistances being ignored:

2.3.1 Current ripple in the load branch

The ripple is defined by (see Fig. 5b)

$$r = \frac{I_1 - I_2}{I_1 + I_2}$$

As experiments have already shown, it holds in good approximation that

$$r = \frac{L_{cr}}{L_{load}}$$

2.3.2 Currents in the load branch

The current in the load branch comprises two components. If I_1 is the maximum value of the ringing discharge current, the two equations in 2.3.1 yield for the currents given in Fig. 5b:

$$I_2 = I_1 \cdot \frac{1 - r}{1 + r}$$

$$I_B = I_1 \cdot \frac{2 \cdot r}{1 + r}$$

$$I_A = I_1 \cdot \frac{1}{1 + r}$$

2.3.3 Maximum current in crowbar branch

As can be seen from the equivalent circuit diagram in Fig. 5a, the spurious components of the currents behave under the above conditions as follows:

$$\left(\frac{i_{cr}}{i_{load}}\right)_{spur} = \frac{L_{load}}{L_{cr}} = \frac{1}{r} ;$$

From this it follows that

$$\hat{I}_{cr} = I_1 \cdot \frac{2}{1 + r} ;$$

2.3.4 Maximum current through the store

For the instantaneous value of the current through the store it holds that

$$i_{co} = i_{load} - i_{cr};$$

It thus follows that

$$\hat{I}_{co1} = I_1 ;$$

$$\hat{I}_{co2} = - I_1 ;$$

2.3.5 Spurious frequency

The spurious frequency, i.e. the frequency of the storage and crowbar branches for times $t > t_1$, is given by the following expression:

$$f_{spur} = \sqrt{\frac{L_{St} + L_{load}}{L_{St} + r \cdot L_{load}}} \cdot f_o ;$$

f_o being the frequency of the ringing discharge.

2.3.6 Voltage at the capacitor

Up to t_1 the maximum voltage at the capacitor is

$$V_{co1} = V_{co} \quad ,$$

V_{co} being the charging voltage. After t_1 one obtains

$$V_{co2} = V_{co} \cdot \sqrt{\frac{L_{St} + L_{cr}}{L_{St} + L_{load}}} \quad ;$$

The time variation of the voltage at the capacitor is plotted in Fig. 5c.

2.4 Calculation with allowance for small ohmic losses

Small ohmic losses can be allowed for approximately. With

$$t^{*} = t - t_1 \; ;$$

$$\delta_2 = \frac{L_{St} + L_{cr}}{R_{St} + R_{cr}} \; ;$$

$$\omega_2 = 2\pi \cdot f_{spur} \; ;$$

$$\delta_3 = \frac{L_{load}}{R_{cr} + R_{load}} \; ;$$

(R = ohmic resistor)

the following equations are then obtained:

2.4.1 Current maximum

$$\hat{I}_1 = V_{co} \cdot \sqrt{\frac{C}{L}} \cdot e^{-\delta t_1}$$

2.4.2 Current in the load for $t > t_1$

$$i_{load} = \hat{I}_1 \cdot \left(\frac{1}{1+r} \cdot e^{-\delta_3 t^{*}} + \frac{r}{1+r} \cdot \cos\omega_2 t^{*} \cdot e^{-\delta_2 \cdot t^{*}} \right) \; ;$$

2.4.3 Current through the store for $t > t_1$

$$i_{St} = \hat{I}_1 \cdot \left(1 - \sin\omega_2 \cdot t^{*} \right) \cdot e^{-\delta_2 \cdot t^{*}} \; ;$$

2.4.4 Voltage at the capacitor for $t > t_1$

$$v_{St} = V_{co} \cdot \sqrt{\frac{L_{St} + L_{cr}}{L_{St} + L_{load}}} \cdot \sin\omega_2 \cdot t^{*} e^{-\delta_2 t^{*}} \; ;$$

3. Trigger system for the crowbar spark gaps

The trigger system and the subdivision of the crowbar system are shown in Fig. 6.
In order to discharge the energy stored in the bank, a trigger signal has to be conveyed to the delay device. This signal immediately generates a trigger pulse at the output 1 which ignites the start spark gaps by way of other auxiliary units. After a set delay of $\Delta t = \frac{T}{4}$, a 12 kV trigger unit is actuated from the output 2. The resulting output pulse of the 12 kV trigger unit is conveyed to the master spark gap by way of a pulse transformer. The master spark gap then actuates 18 two-stage Marx generators by way of 18 cables. Each Marx generator supplies 14 crowbar gaps with the necessary trigger pulse.

3.1 Delay device

This device, produced in series in the IPP, allows a time delay between the outputs 1 and 2 which can be set in steps of 0.1 μsec up to a value of 110 μsec. The pulse provided has the following data:

$\hat{V}$ = + 200 V
Risetime = 10 nsec
Δt = 2 nsec, jitter absolute

3.2 12 kV trigger unit

In this unit, a capacitor is discharged by way of a hydrogen thyratron to produce a high-voltage pulse which is conveyed to the input of a 50 Ω cable across a separator spark gap. At the input of the cable, the pulse has the following values:

$\hat{V}$ = - 12 kV
Risetime = 17 nsec
Δt = 2 nsec, jitter absolute.

The 15 m long, shielded coaxial cable (RG8U) conveys the pulse to the trigger electrode of the master gap via a pulse transformer with a transmission ratio 1 : 2 and the limiting frequency f_g = 20 MHz. The peak voltage at the output of the pulse transformer is 42 KV.

3.3 Precautions against premature breakdown

The trigger units in the crowbar system are fitted with electron tubes and are highly sensitive to premature breakdown. Premature breakdown is particularly liable to be caused by voltage transient when the start gaps are triggered. The following precautions were taken:

1) The delay device and the 12 kV trigger unit were installed in a well-shielded room.
2) The hydrogen thyratron in the trigger unit was operated at an anode voltage which is 2 kV below the permissible value.
3) The 12 kV trigger unit was insulated from the bank by a separator spark gap in addition to the pulse transformer.
4) The coaxial cable between the trigger unit and the master gap was shielded.

These precautions afford adequate protection against premature breakdown. Since the bank has been in operation (4.300 discharges) there has been no premature breakdown.

3.4 Master spark gap

3.4.1 Choice of master gap

The choice of master gap was governed by the demand that this component has a certain stability to voltage transients when the start switch is triggered. For this reason the ratio of operating voltage to static breakdown voltage in the master gap was also chosen rather low, namely 25 kV/40 kV = 0.625.

A cascade spark gap is less suitable for this purpose because the pulse transformer would greatly hamper the dynamic control.

A trigatron was tested as to its suitability. The principle and dimensioning of trigatrons has already been discussed at length by various authors (L 4), (L 5). These authors recommend a ratio of 0.5 for the breakdown voltages between the trigger pin and the cold electrode and between the trigger pin and the hot electrode in order to obtain a small jitter in an operating range of $V_1 = 0.5\ V_{Dstat}$ to V_{Dstat} (see Fig. 7, curve a). Designing a trigatron on these lines for $V_{Dstat} = 40$ kV would call for a very large bore in the cold electrode (for admitting the trigger pin). A thin pin in a large bore would disturb the uniformity of the electric field in the steady state so much, however, that adequate protection is no longer afforded against premature breakdown.

A swinging trigatron was therefore used as master gap. This switch has a range from 0.35 V_{Dstat} to V_{Dstat} and a jitter < 10 nsec and is immune to premature breakdown (see Fig. 8, curve b).

3.4.2 Mechanical design

The mechanical design is shown in Fig. 9. The cold electrode contains a tungsten pin enclosed in Teflon. The Teflon case is surrounded by the trigger electrode. The dimensions are such that the breakdown voltage between the trigger electrode and cold electrode is 0.7 times the static breakdown voltage of the spark gap. In a trigatron, this space between the trigger electrode and cold electrode is filled with an insulating material, thus making the electric field non-uniform. In our case, the space was filled with a protolin-graphite mixture which has a specific DC resistance of $10^4\ \Omega$/cm. This means that in the steady state there are two conducting surfaces opposite one another which do not cause any disturbance of the uniform field. If, however, a trigger pulse is applied to the trigger electrode, it encounters the same conditions as in the ordinary trigatron owing to the high resistance between the trigger electrode and cold electrode. The complete master gap is shown in Fig. 8.

3.4.3 Mode of operation

The circuit diagram of the master gap is given in Fig. 10. This spark gap is operational when the cable charging voltage of 25 kV is present at the electrode A. Breakdown takes place when a pulse of opposite polarity and with a steepness of S' = 2.5 kV/nsec is applied to the trigger electrode D. Soon after (at about 5 kV) a current flows across the creepage gap D-C (1 mm) and prepares the gap D-A for a jitterless breakdown by irradiating the space between D and A. After the breakdown from D to A, the electrode D exceeds the value of U_L owing to the stray capacitance C_S. At D, a value of 1.4 U_L was measured. This voltage leads to breakdown from D to B, thus making the connection A→D→B. The variation of the potential at the electrode D during the ignition process is plotted in Fig. 11.

Owing to the swinging of the electrode D, the range of the correct sequential triggering (Längstriggerung) can be extended. In our case the ratio $U_{D-B} : U_{D\rightarrow A}$ can be $0.5 \cdot 1.4 = 0.7$. The principle of this swinging trigatron has been taken practically from the swinging cascade (9).

3.4.4 Special properties of the switch

In this switch, the triggering sequence described, and hence a small jitter, is ensured in an operating range from 0.35 V_{Dstat} to V_{Dstat}. The switching process is shown in Fig. 7, curve b. If the operating voltage approaches the static breakdown voltage, the breakdown from D to C coincides in time with the breakdown from D to A. The breakdown from D to A is thus no longer prepared for by irradiation, and so the jitter is slightly higher.

3.5 Marx generators

3.5.1 Definition of problem

For triggering the 252 crowbar spark gaps a pulse with a peak voltage of 125 kV and a steepness of S = 0.3 kV/nsec. is required. These data call for a pulse voltage of 70 kV at the input of the trigger cable. Because space was scarce, the charging voltage for the necessary generator was kept low by using two-stage Marx connection.

Fourteen crowbar gaps are supplied by one trigger generator. This means that eighteen generators are required for the whole bank.

3.5.2 Construction and mode of operation

The capacitor for the generator was of the type Cip 75/1.1 - 3 manufactured by Siemens-Schuckert. The data are as follows:

Charging voltage, permissible	48 kV
Capacitance	1.1 μF
Self-inductance	50 nlt
Discharge current, permissible	100 kA
Stored energy, permissible	1.25 kJ
Eigenfrequency	680 kHz
Volume	22 l
Energy density	0.06 J/cm^3

A generator consists of two capacitors which are charged in parallel to 35 kV. On arrival of the trigger signal from the master gap, the two capacitors are connected in series across two spark gaps. The electrodes of the spark gaps are 80 mm in diameter, and the interelectrode distance is 20 mm. This produced a static breakdown voltage of 57 kV. Only the bottom gap, for which a trigatron was used, is triggered (see Fig. 12). This results in overvoltage at the top spark gap, thus causing breakdown. If fourteen trigger cables (Type F & G 4.9/17.3) each 29 m long are connected to a Marx generator, one obtains at the open cable end a voltage pulse with the following data:

Pulse voltage	125 kV
Pulse rise (10 % 90 %)	350 nsec.
Pulse duration (5o % - 5o %)	500 nsec.

The energy content of a Marx generator is sufficient to supply any crowbar spark gap with an energy of 96 joules. During the ignition process, the ferrite cores of the crowbar gap become saturated. This causes short-circuiting at the cable terminal. In this state, the generator is loaded as follows:

Peak current of one generator	46 kA
Current load of one cable	3,3 kA
Discharge frequency	212 kHz.

4. Crowbar Switch

4.1 Requirements

General requirements that have to be met by a crowbar switsch are:

4.1.1 The ability to switch at the moment when no or little voltage is present across the switch (zero voltage in an oscillating discharge).

4.1.2 The inductance of the switch must be low relative to that in the load branch (see Fig. 2) so that the ripple of the crowbar discharge ($r = \frac{L_{cr}}{L_{load}}$) is small.

4.1.3 The ohmic resistance must be of the order of or smaller than that in the load branch in order to obtain as long a confinement time as possible.

4.1.4 The switch also has to transfer the current fast even at low voltages in order to prevent the energy returning to the store.

In addition, the following requirements have to be met in the case of the 2.6 MJ bank:

4.1.5 The switch should operate under normal pressure like the start spark gap.

4.1.6 The limited space available in the already installed bank should be sufficient to accomodate the switch and allow subsequent incorporation without any great difficulty.

4.1.7 The lifetime should be about the same as that of the other components.

4.2 Choice of switch

Spark gaps of the type used in capacitor banks as start switches (trigatron, cascade spark gaps, field distortion cascade gaps) have a maximum operating range of 0.2 U_{Dstat} to U_{Dstat}. They thus fail to meet the requirement stated under 4.1.1 and are not suitable as crowbar switches.

The reason why a plasma switch or vacuum spark gap cannot be used is given in 4.1.5.
The series connection of two trigatrons according to Koch (6) was not adopted because experience with such an arrangement is only available for a bank charging voltage of 18 kV. Operation at a charging voltage of 40 kV seems to present problems.
Our choice fell on the principle of the ferrite-decoupled two-electrode spark gap as proposed by Kaufmann and Wilhelm (7).

4.3 Crowbar spark gap

The design and mode of operation of the crowbar spark gap is described only briefly here. A detailed account is given in the report IPP 4/32 (8), (11).
The design was largely governed by the limited space available in the already installed bank. A photograph of the built-in spark gap is shown in Figure 14. Figure 2 indicates how it is incorporated in the circuit.
The gap D-E must withstand the oscillating voltage of 40 kV max. A static breakdown voltage of 56 kV was set as a necessary precaution. In order to breakdown this gap at zero voltage, it is necessary to have at E a voltage pulse > 56 kV (independent of the steepness of the pulse).

The impedance in the circuit parallel to the electrodes F and D was increased by inserting 30 ferrite cores of the type Krupp D1 S2. Since the trigger voltage attainable at E depends on the steepness of the applied pulse, the trigger pulse was conveyed across the pulse sharpening spark gap F-E.

The pulse at F with a relatively gentle slope is used at the same time for premagnetizing the ferrite cores. This means that the pulse at E always encounters the same initial magnetic conditions and the available voltage-time area is greater, which results in a higher pulse.

As a result of the premagnetization, it was possible to attain pulses of 80 kV at E in the described bank. This is sufficient for proper breakdown.

5. Loading due to premature breakdown of the crowbar spark gaps

The whole crowbar system was designed to provide a high degree of protection against spurious breakdown of the crowbar switches. This is necessary because such breakdown may cause damage to parts of the bank.
In a spurious breakdown the greatest likelihood of damage occurs when the crowbar spark gap breaks down at the same time as the start switch. The resulting current load for the components involved (capacitor and start spark gap, crowbar spark gap, cable) can be seen in Fig. 13. The damping due to ohmic resistances was not taken into account.

5.1 Premature breakdown of the electronic trigger units or master spark gap

All 252 crowbar switches are triggered too soon. In the normal case, the bank discharges to a load with a total inductance corresponding to 3.026 μH per single circuit. In the event of a disturbance of this kind, the whole bank would discharge to the 252 crowbar circuits. The inductance of such a circuit is 0.52 μH, which is considerably smaller. The following current loads occur with a frequency of 62 kHz (Fig. 13a):

5.1.1 Maximum current through the store and across the start spark gap I_{ST} = 207 kA.
5.1.2 Maximum current across the crowbar spark gap I_{CR}= 180 kA.
5.1.3 Maximum current through three load cables I_{CA} = 27 kA.

5.2 Premature breakdown of a Marx generator

This causes premature breakdown of 14 crowbar spark gaps. The current loads received by each crowbar gap from its own capacitor group are stated in 5.1. The other 17 groups would supply each crowbar spark gap with a frequency of 26.7 kHz. Vector addition of the load currents yields the following values (Fig. 13b):
5.2.1 Maximum current through the store and across the start spark gap I_{ST} = 207 kA.
5.2.2 Maximum current across the crowbar spark gap I_{CR} = 320 kA.
5.2.3 Maximum current through three load cables I_{CA} = 245 kA.

5.3 Premature breakdown of one crowbar spark gap

The crowbar spark gap is again supplied by its own group in accordance with 5.1. At the precollector, this group is connected with another thirteen groups, which supply an additional current with a frequency of 28.6 kHz. The remaining 238 groups no longer load the switch. Vector addition of the load currents yields the following values (Fig. 13c):
5.3.1 Maximum current through the store and across the start spark gap I_{ST} = 207 kA.
5.3.2 Maximum current across the crowbar spark gap I_{CR} = 400 kA.
5.3.3 Maximum current through three load cables I_{CA} = 340 kA.

6. Summary

The eyperimental investigations for developing a ferrite-decoupled crowbar spark gap have shown that such spark gaps constitute an extremely reliable and simple type of switch with a large operating range and small jitter. This is confirmed by practical experience with the 252 crowbar spark gaps incorporated in the 2.7 MJ bank. Since modification of the bank 4300 trouble-free discharges have been performed.

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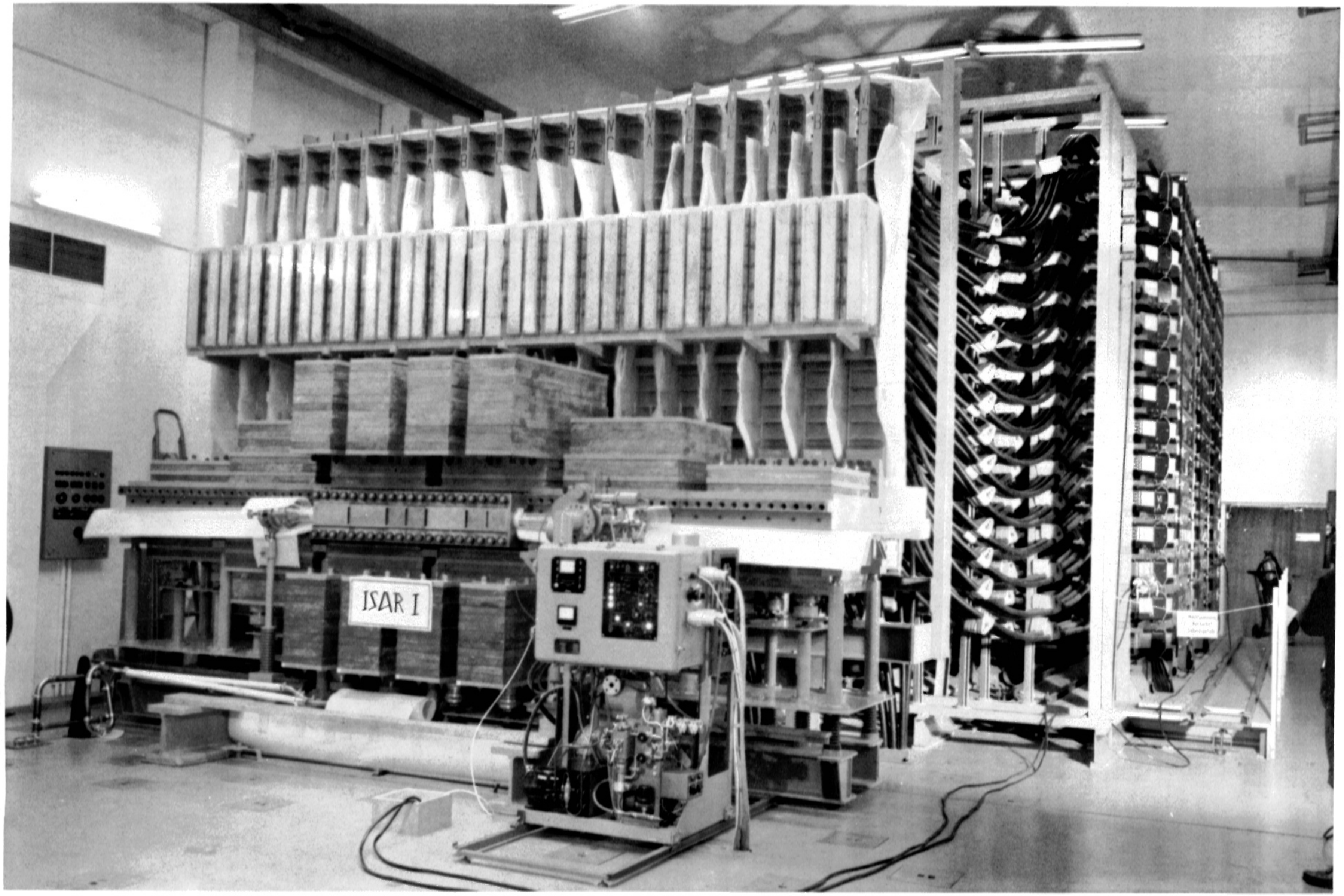


P 020 1,5/2,6 MJ - Theta-Pinch Isar I
Front view

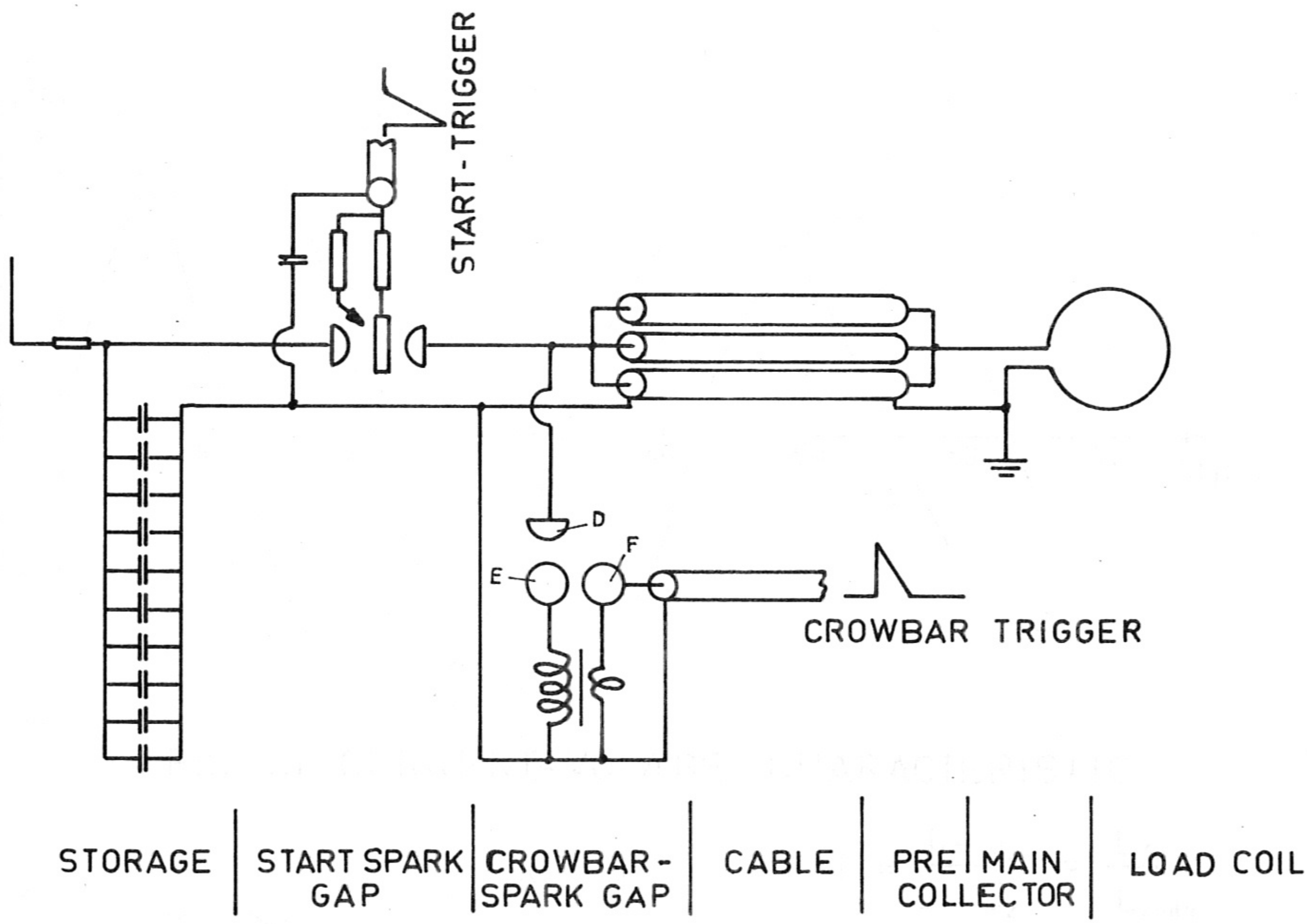


FIG. 2 CIRCUIT DIAGRAM OF ONE GROUP OF ISAR I.

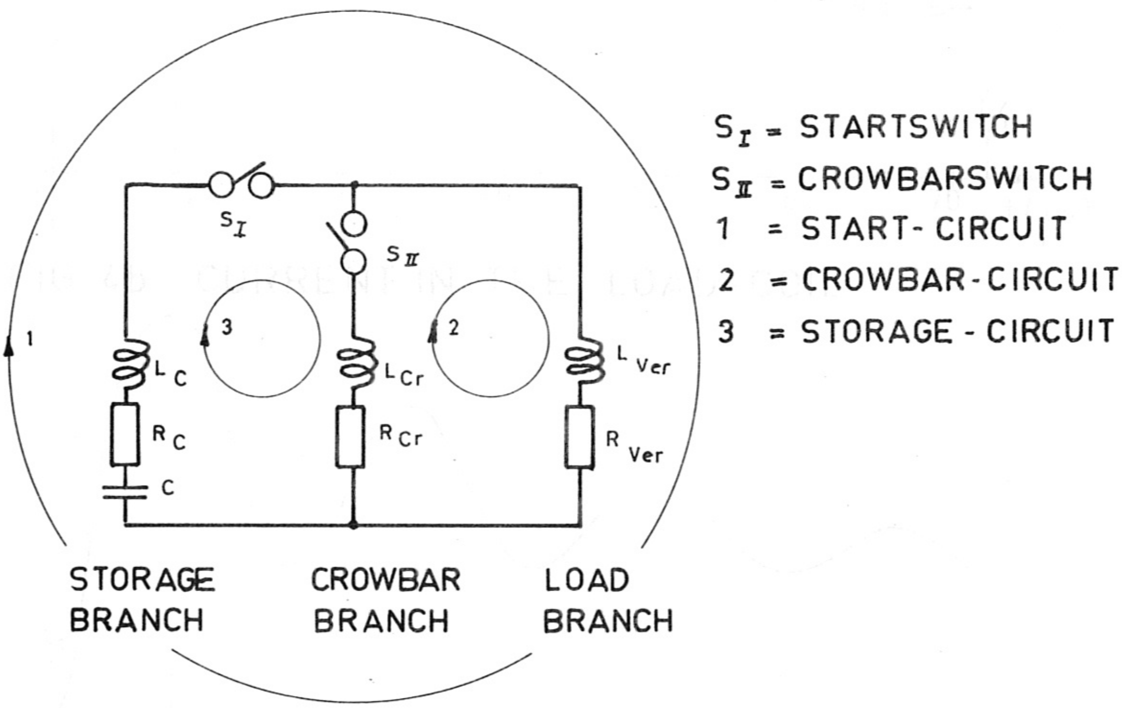


FIG. 3 PRINCIPLE CIRCUIT DIAGRAM OF ISAR I.

$L_C = 0{,}794$ nH;	$L_{Cr} = 1{,}31$ nH;	$L_{Ver} = 1{,}1781$ nH
$R_C = 0{,}0188$ mΩ	$R_{Cr} = 0{,}043$ mΩ;	$R_{Ver} = 0{,}158$ mΩ
$C = 3{,}36$ mF;		

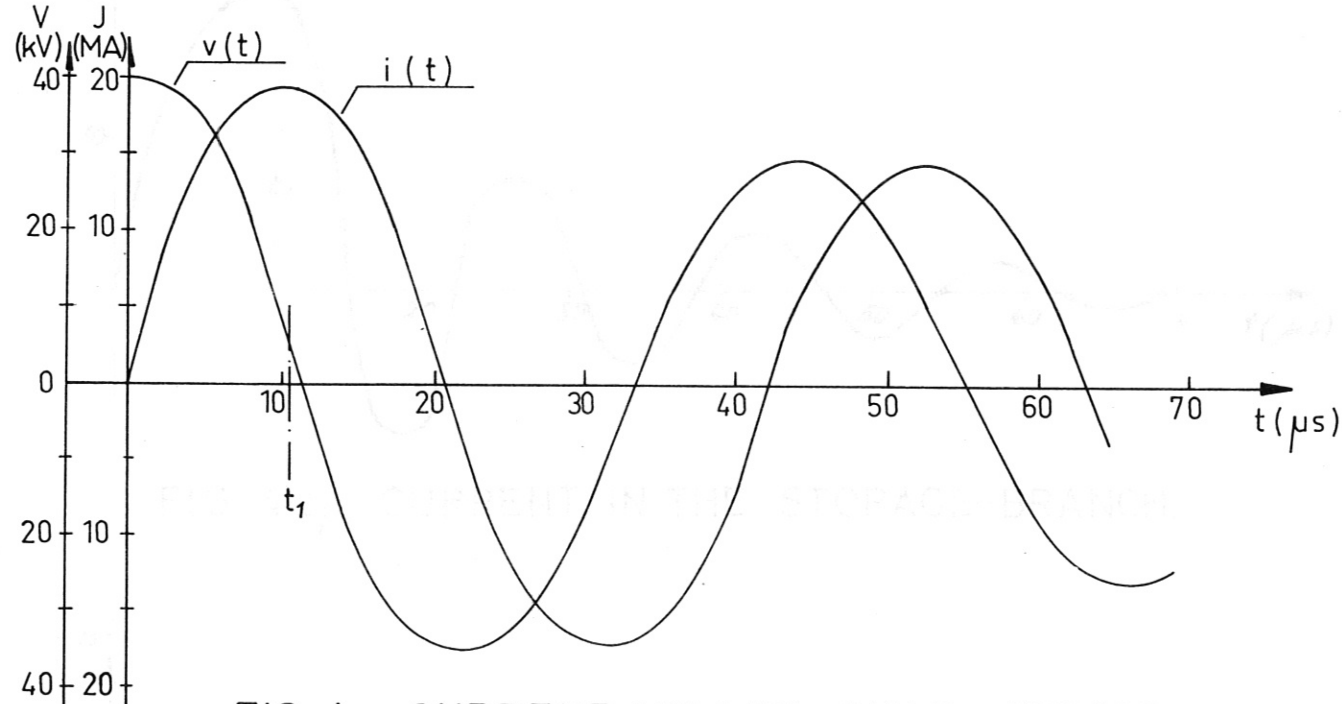


FIG. 4a CURRENT-VOLAGE CHARACTERISTIC

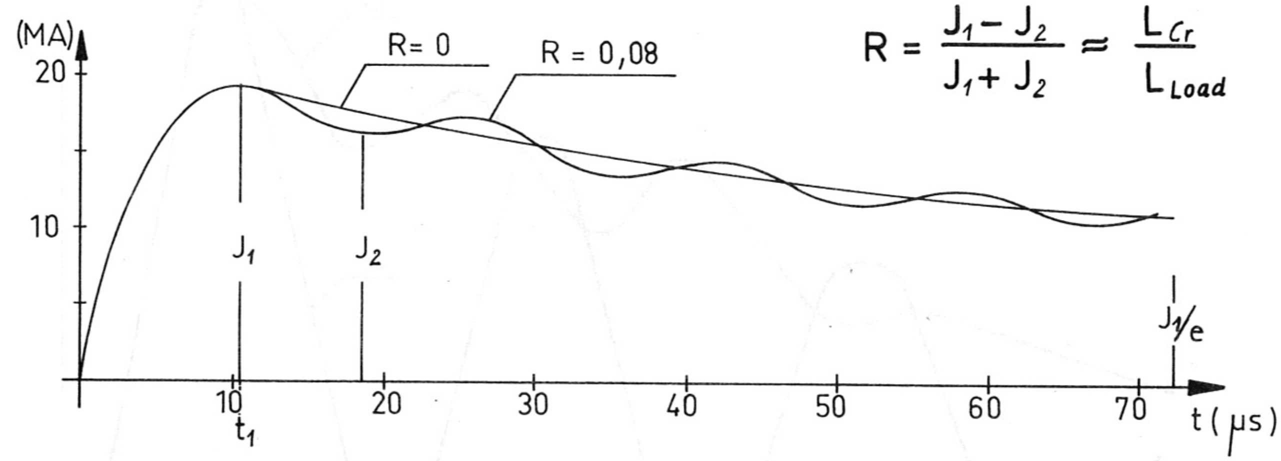


FIG. 4b CURRENT IN THE LOAD-COIL

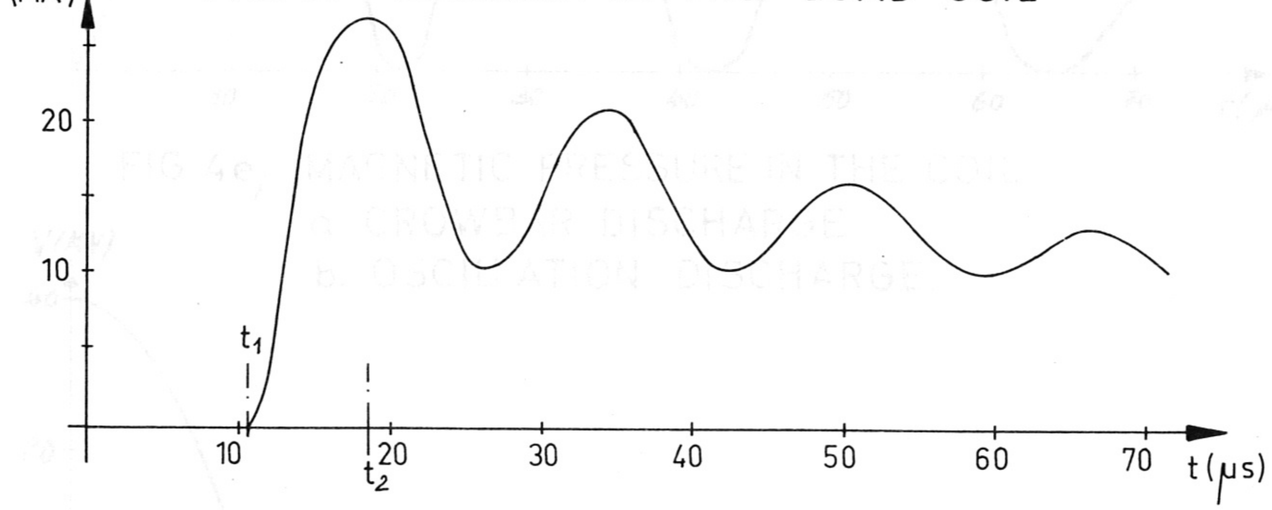


FIG. 4c CURRENT IN THE CROWBAR-BRANCH

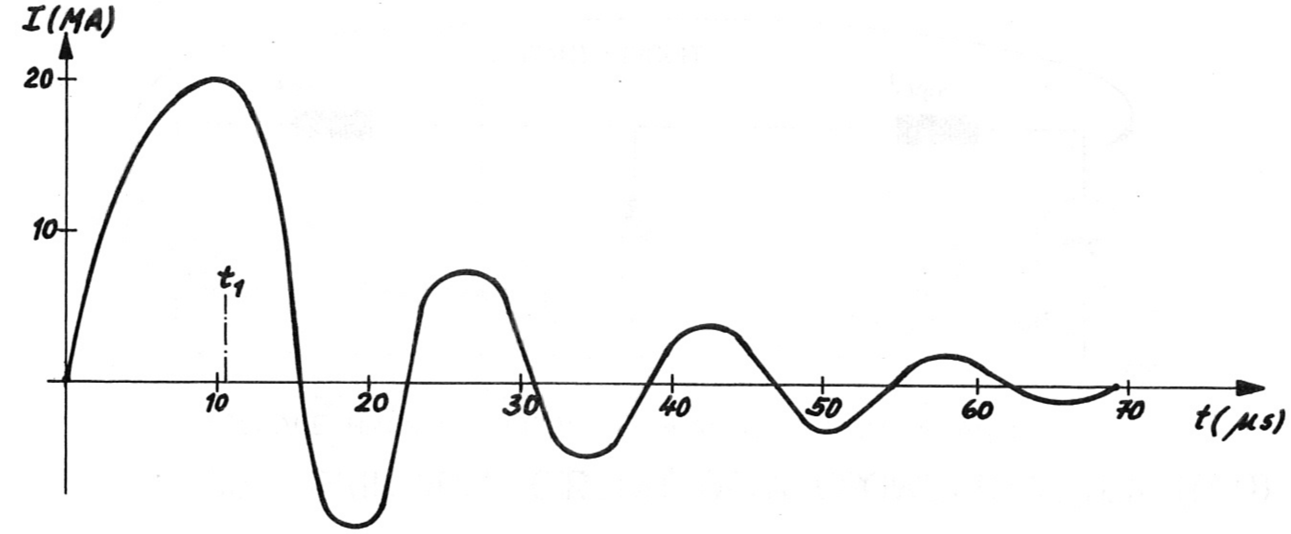


FIG. 4d$_i$ CURRENT IN THE STORAGE-BRANCH.

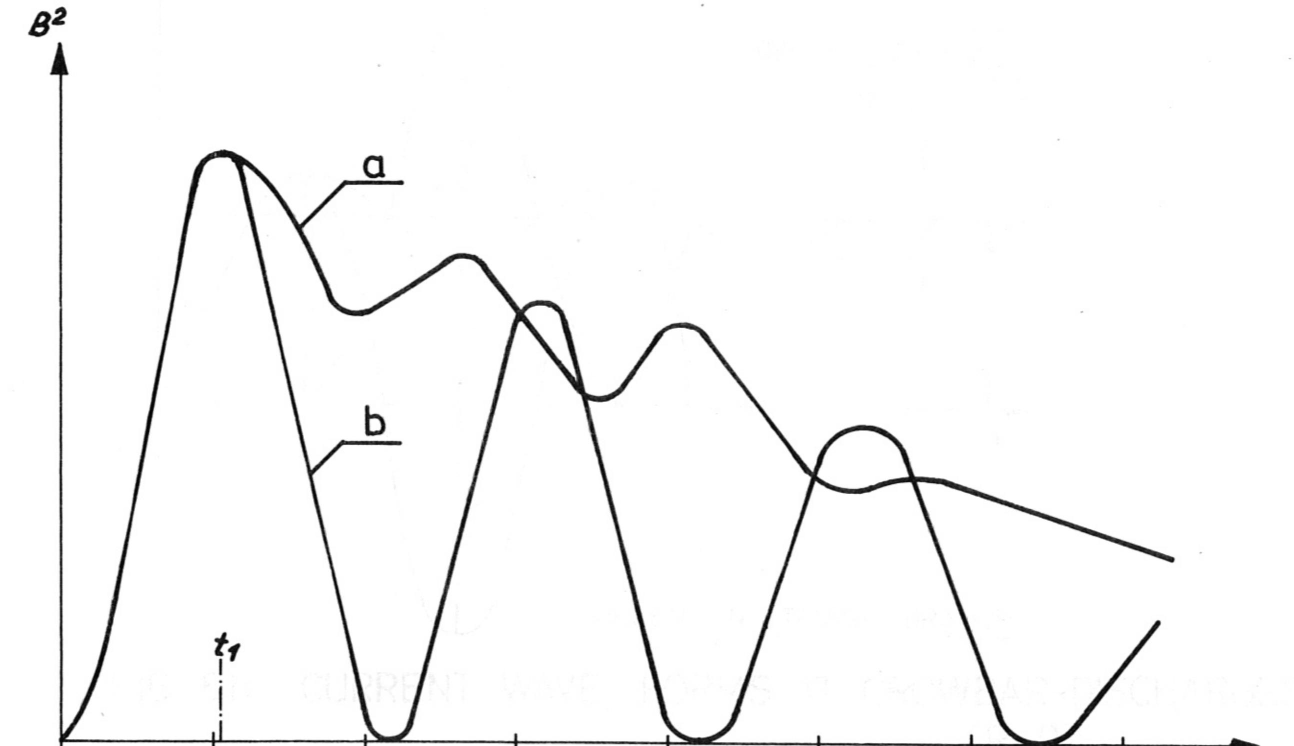


FIG. 4e$_i$ MAGNETIC PRESSURE IN THE COIL.
a. CROWBAR DISCHARGE.
b. OSCILLATION DISCHARGE.

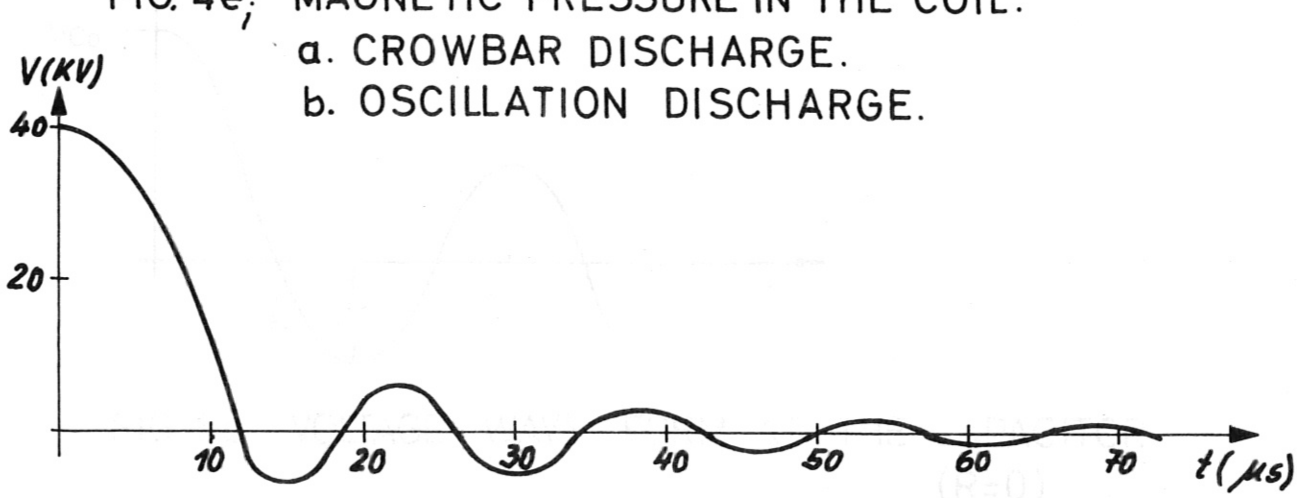


FIG. 4f$_i$ VOLTAGE AT CAPACITOR.

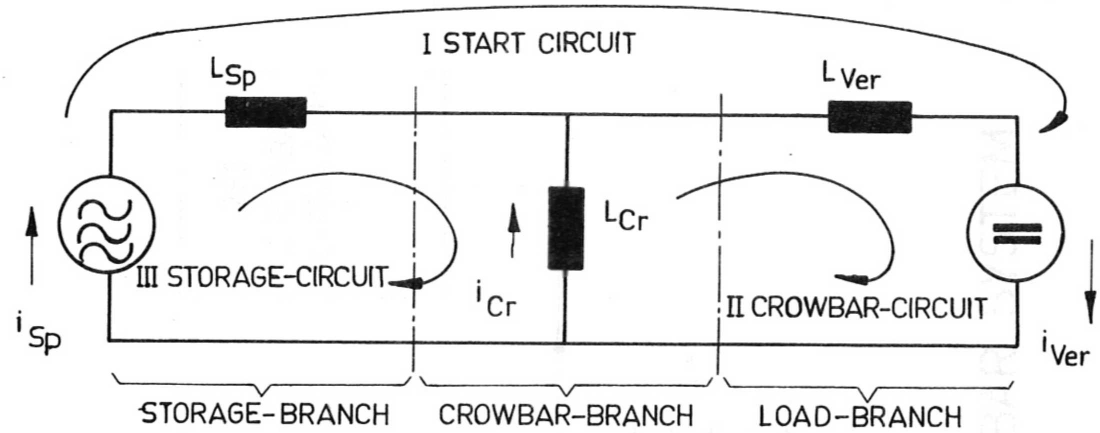


FIG. 5a PRINCIPLE CIRCUIT OF A CROWBARSYSTEM (R=0)

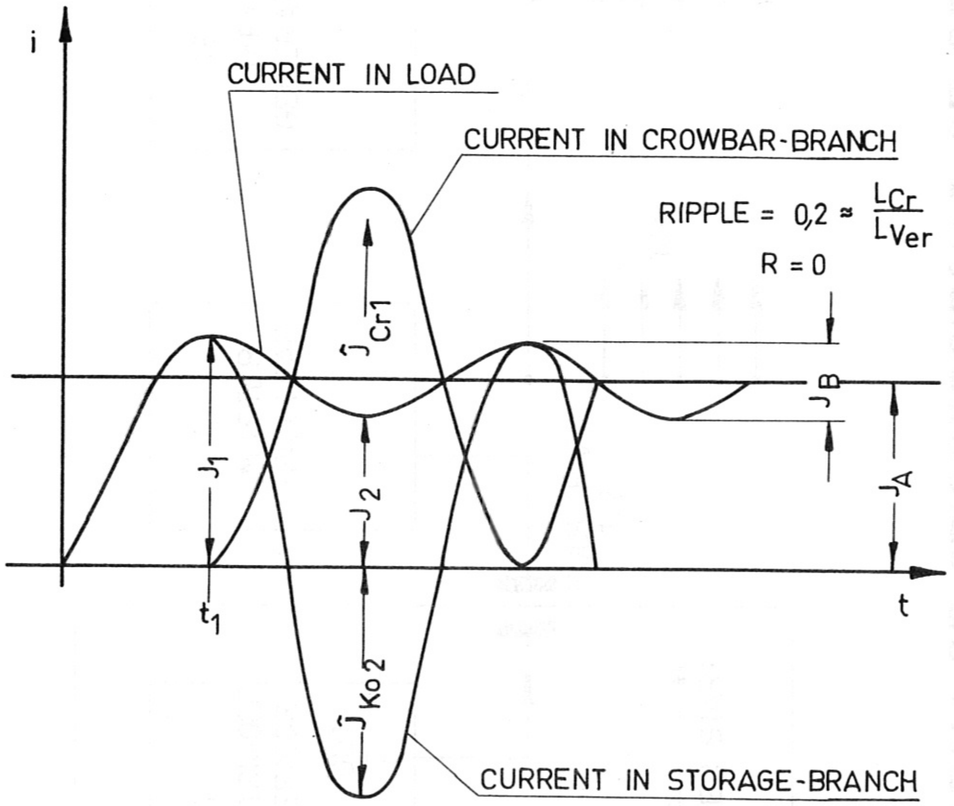


FIG. 5b CURRENT WAVE FORMS AT CROWBAR-DISCHARGES (R=0)

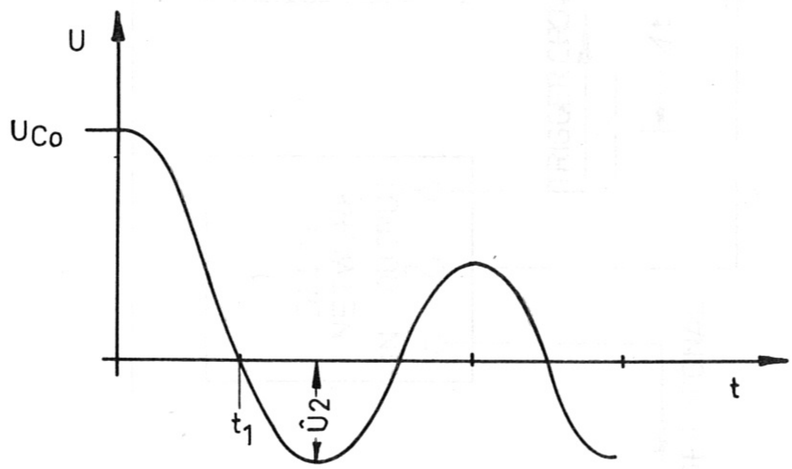


FIG. 5c VOLTAGE WAVE FORM AT THE CAPACITOR (R=0)

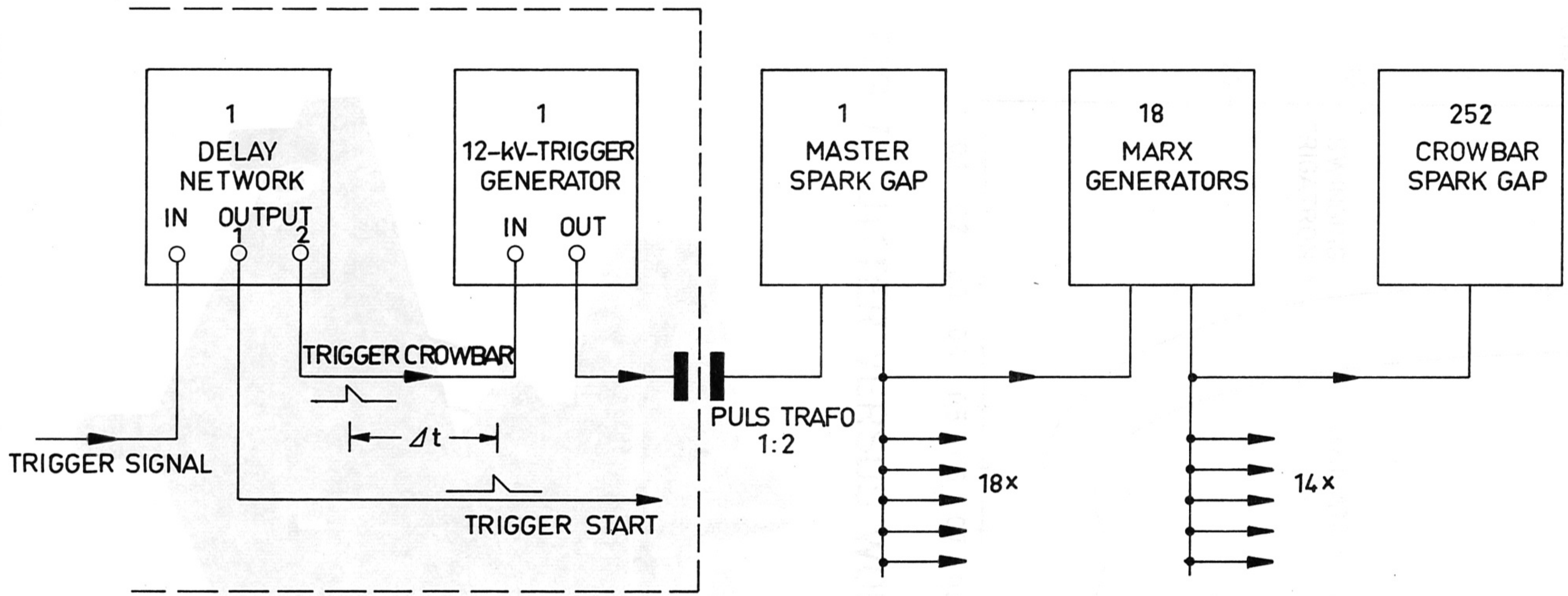


FIG.6 CIRCUIT DIAGRAM OF TRIGGERCIRCUIT OF CROWBAR SYSTEM

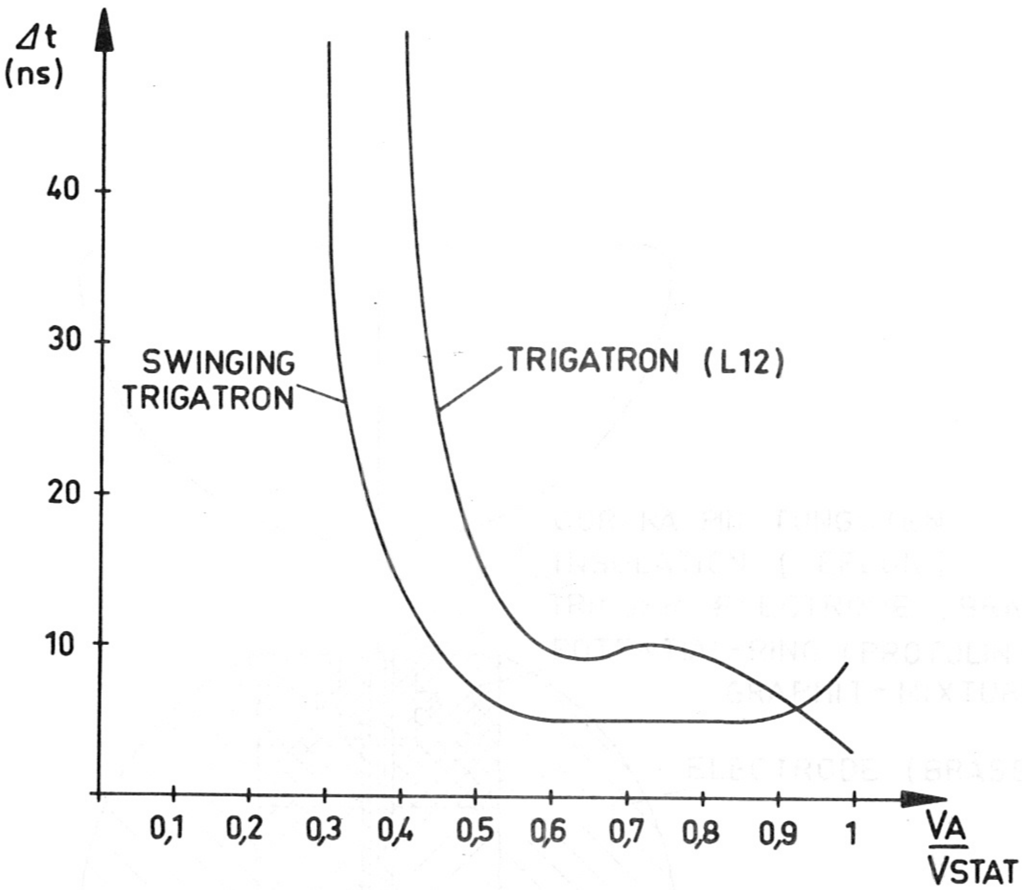


FIG. 7 JITTER VERSUS WORKING RANGE

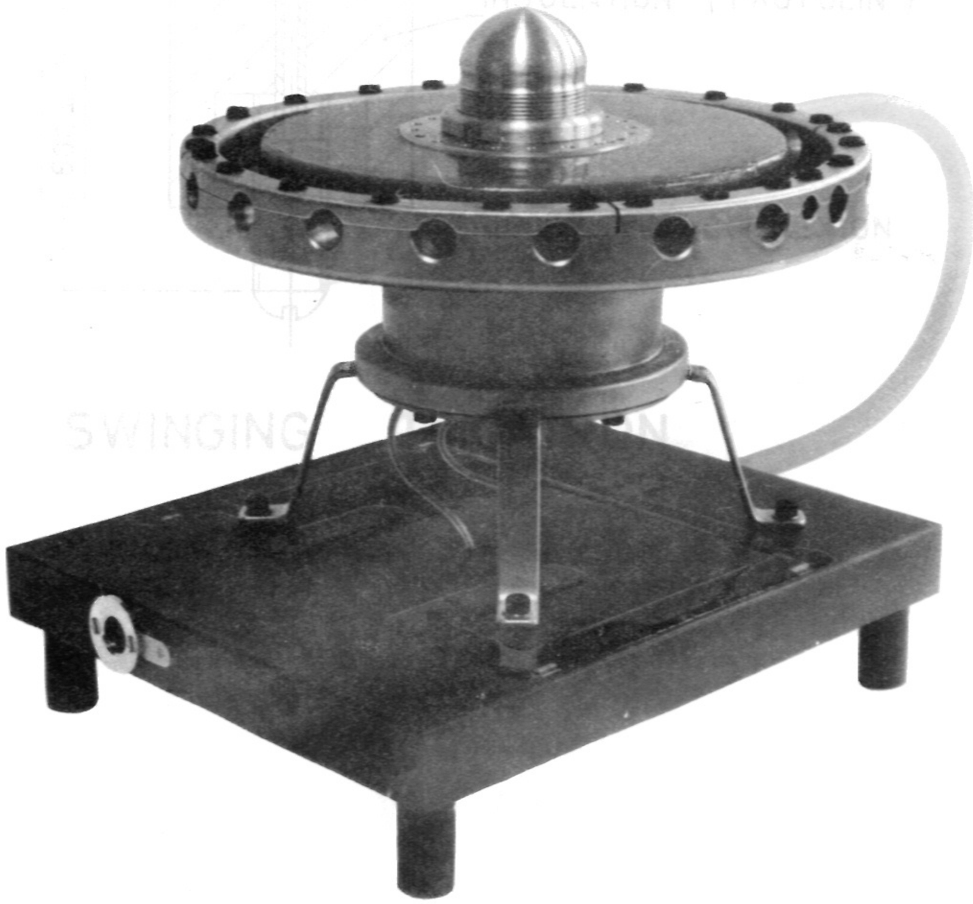


FIG. 8 SWINGING TRIGATRON

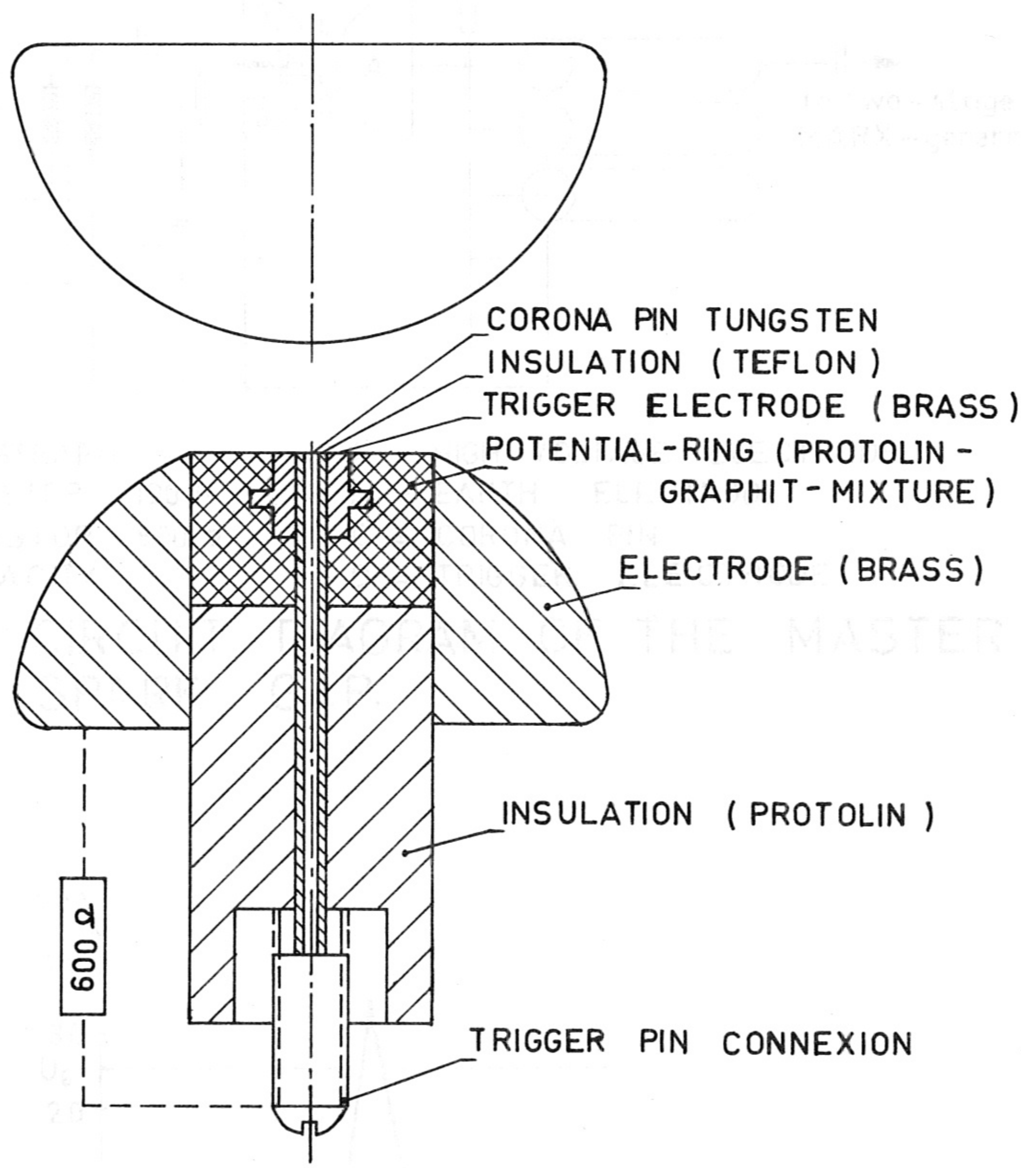
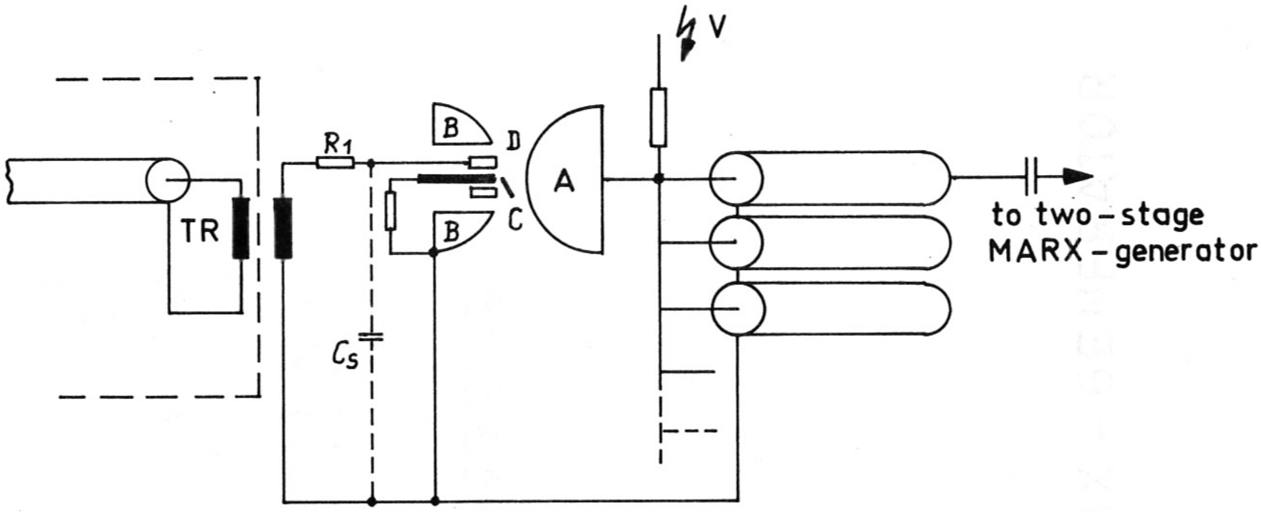


FIG. 9 SWINGING TRIGATRON



TR = PULSTRAFO
R$_1$ = RESISTOR 100 Ω
R$_2$ = RESISTOR 600 Ω
C$_s$ = CAPACITY

A = HIGH-VOLTAGE ELECTRODE
B = EARTH ELECTRODE
C = CORONA PIN
D = TRIGGER ELECTRODE

FIG. 10 CIRCUIT DIAGRAM OF THE MASTER SPARK GAP.

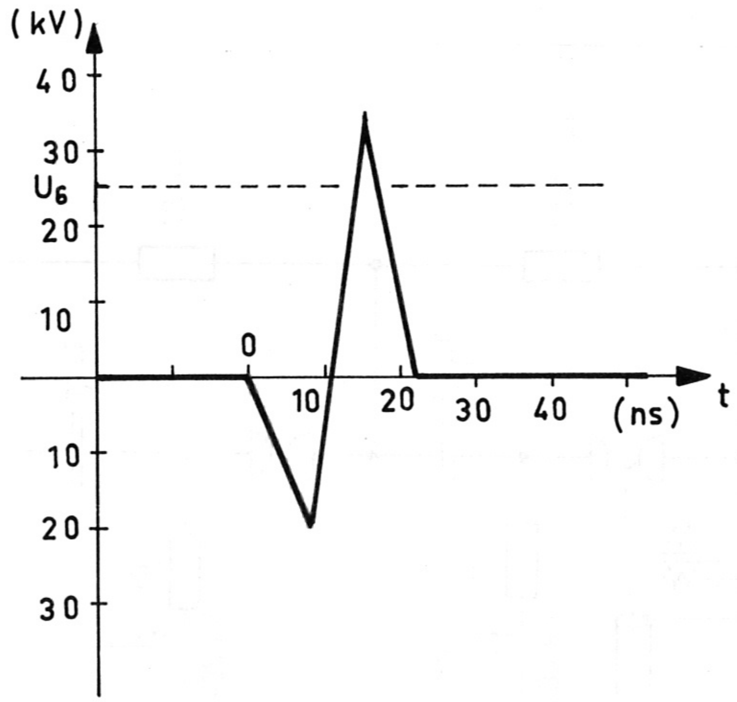


FIG. 11 VOLTAGE WAVE FORM AT THE TRIGGER-ELECTRODE DURING TRIGGERACTION

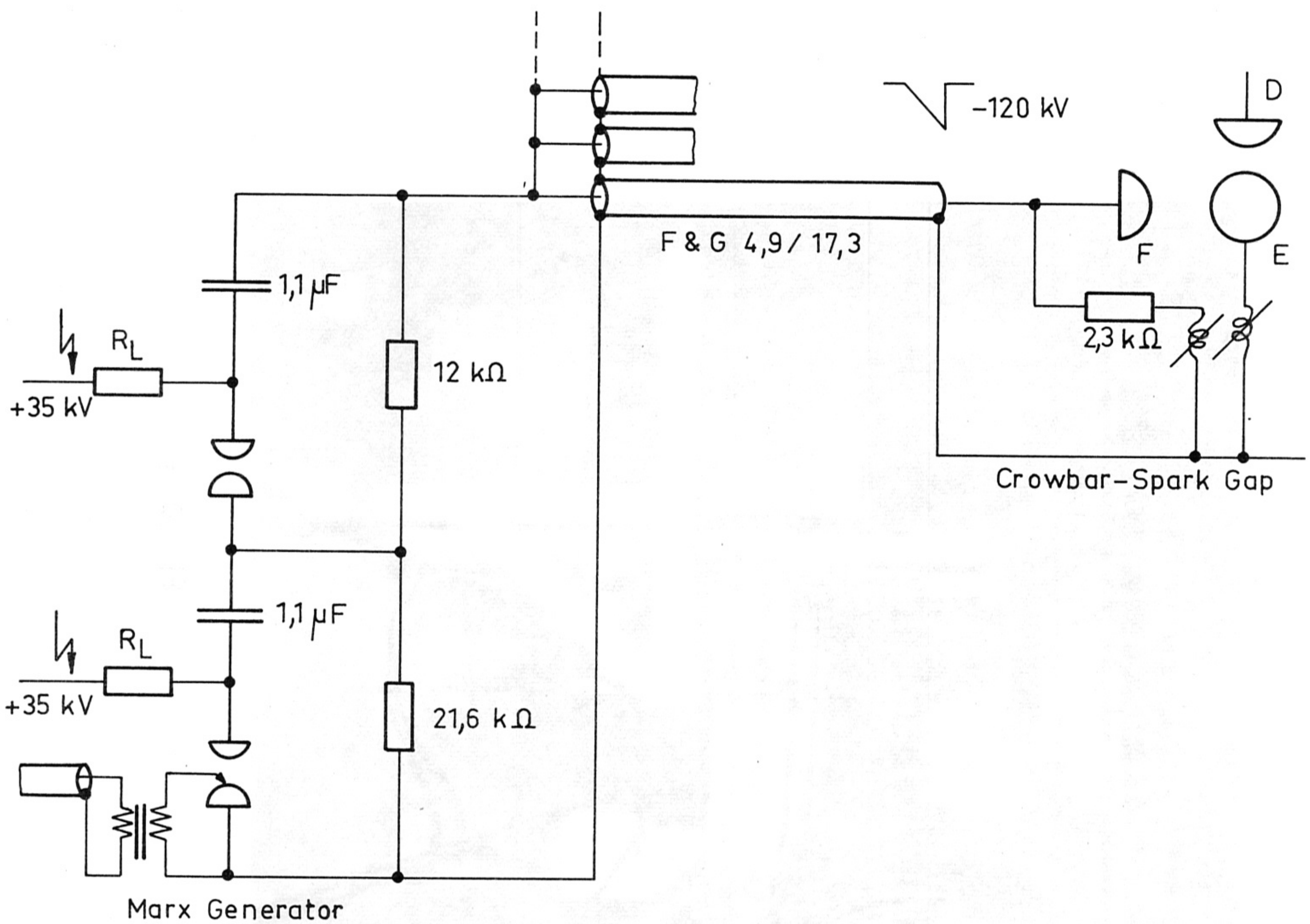


Fig. 12 CIRCUIT DIAGRAM OF MARX - GENERATOR

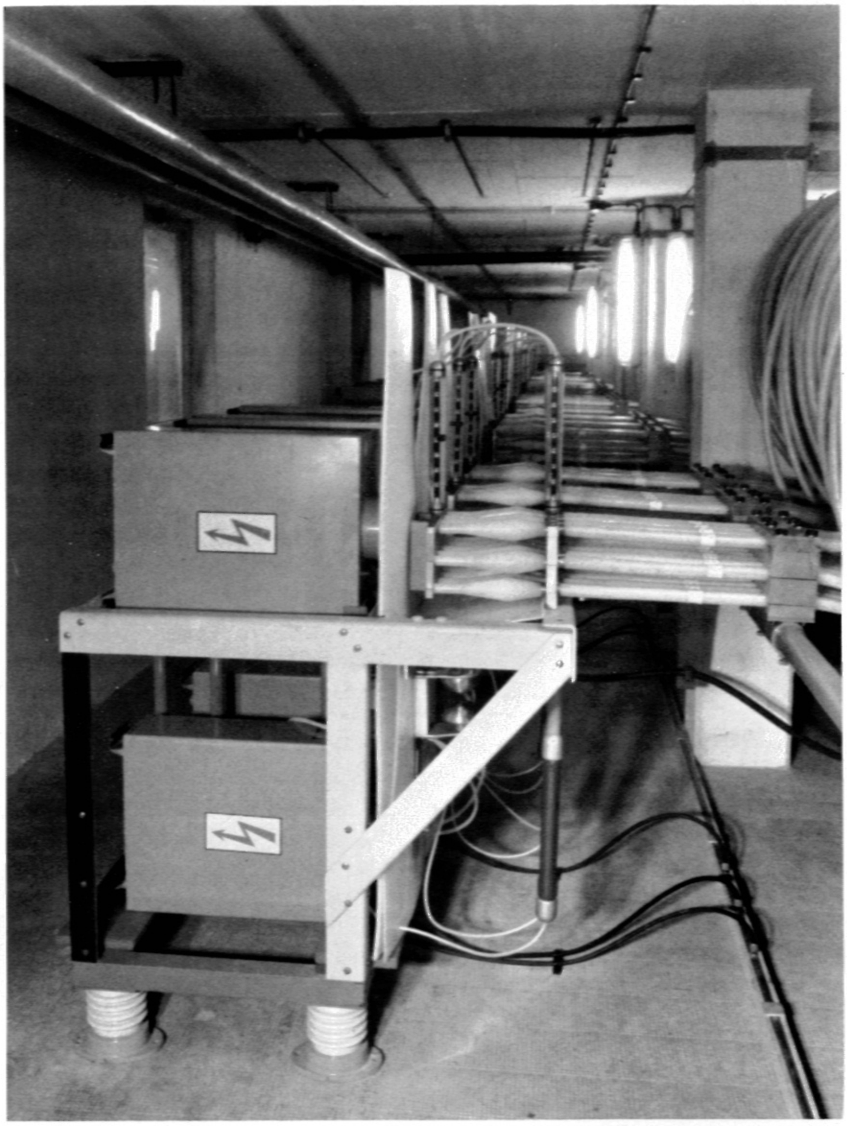
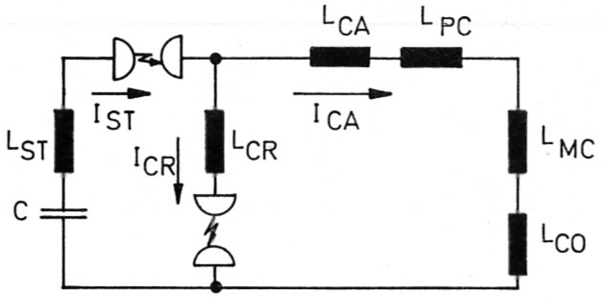


FIG. 13

Installed Marx-generators



CAPACITOR	C	= 13.3	μF
STORAGE	L_{ST}	= 0.2	μH
CABLE	L_{CA}	= 0.231	μH
PRE-COLLECTOR	L_{PC}	= 0.241	μH
MAIN-COLLECTOR	L_{MP}	= 0.336	μH
LOAD-COIL	L_{CO}	= 2.018	μH
CROWBAR	L_{CR}	= 0.33	μH

FIG. 14a

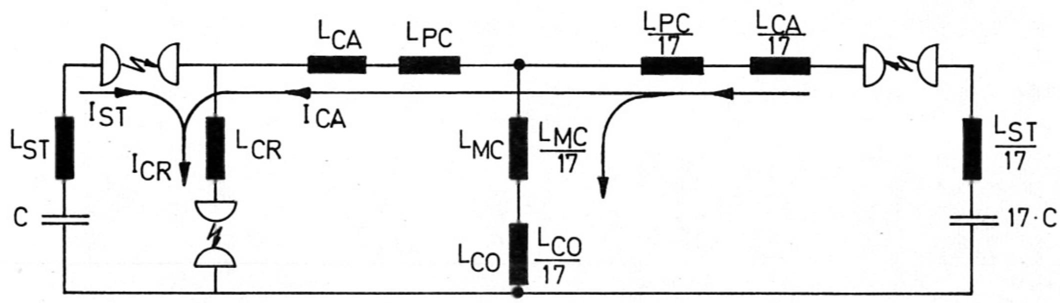


FIG. 14b

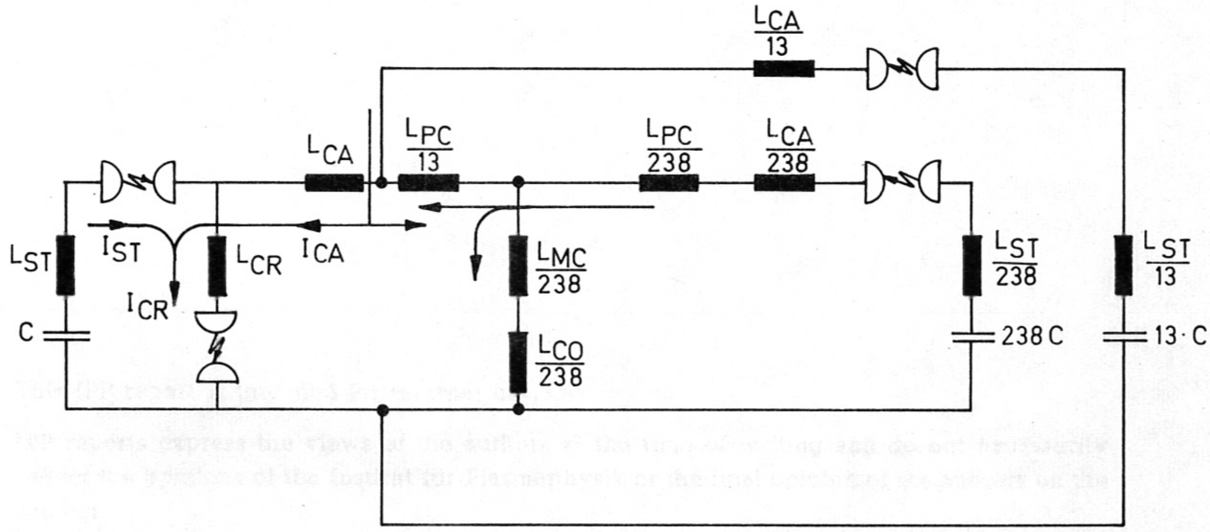


FIG. 14c

FIG. 14 EQUIVALENT CIRCUIT DIAGRAMS FOR PREMETURE TRIGGERING