PICK-UP EXPERIMENTS

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1. INTRODUCTION

The voltage and the current at various points in high voltage pulsed system are measured by special devices called pick-ups. Devices picking up the electric field are called capacitive pick-ups, whilst inductive pick-ups react on variations of the magnetic field. We want to compare the answers given by these different pick-ups and see whether the signal must be integrated for observation or not.

For this purpose the pick-ups will be tested in one single test set-up, which mainly consists of a pulsed high voltage cable fired from another charged cable. The pick-ups will be placed in a reflection free housing connected to the pulse cable. An end resistor terminates the pulse cable.

So we shall start first with the theoretical point of view. Then we shall test our circuit and we shall see what are the eventual reflections or mismatchings. Finally, we shall use high voltage pulses and we shall compare what we obtain with theory, because we want to know perfectly whether parasitic effects like oscillations are coming from the pick-ups or not and how we can get rid of them.

2. THE THEORY OF THE PICK-UP CIRCUITS

We shall see here some equivalent schemes of our pick-up devices and the responses of these pick-ups for different shapes of input pulses.

2.1 Inductive Pick-up

The internal conductor of the coaxial cable near the inductive pick-up produces a variation of magnetic flux in the inductance and we shall see what is the voltage across a resistance R

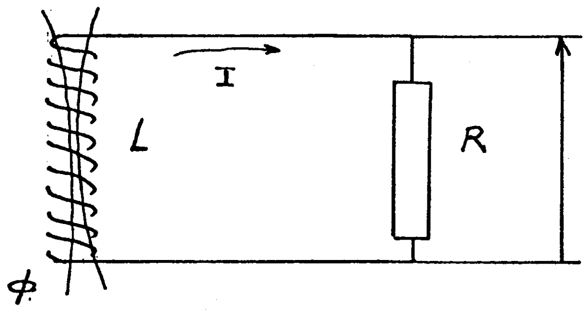


Fig. 1 The L-R circuit

The equations are : $v_S = RI$

$$RI + L\frac{dI}{dt} + M\frac{dJ}{dt} = 0$$

where

J = Current in the primary circuit or line

I = Current in the secondary circuit or pick-up

M = Mutual inductance

2.1.1 Response to a square pulse signal.

If we take $J = I_0 \frac{1 - e^{-ap}}{p}$ in using Laplace transform,

we obtain :

$$v_S = - MI_0 \frac{1 - e^{-ap}}{1 + \tau p} \quad \text{with} \quad \tau = \frac{L}{R}$$

and the responses are given below.

$$v_S = - \frac{MI_0}{\tau}\left[e^{-t/\tau} u(t) - e^{-\frac{t-a}{\tau}} u(t-a)\right]$$

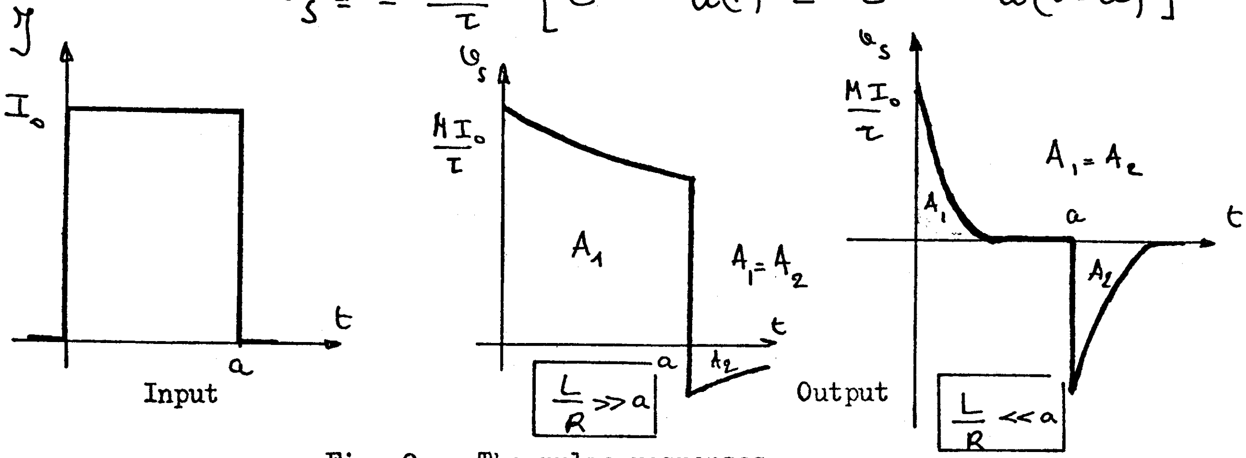


Fig. 2 The pulse responses.

So we see that for a small $\tau = \frac{L}{R}$ we need an integrator which shall give the following signal :

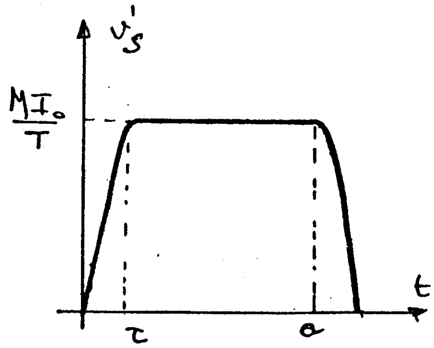


Fig. 3 The pulse response with an integrator for small $\tau = \frac{L}{R}$

2.1.2 Response to a pulse with a certain rise time

We have then $$\mathcal{J} = I_o \frac{1 - e^{-ap}}{p^2}$$

we deduce : $$v_s(p) = - M I_o \frac{1 - e^{-ap}}{p(1+\tau p)}$$

$$v_s(t) = - \frac{M I_o}{a} \left[(1 - e^{-t/\tau})\, u(t) - (1 - e^{-\frac{t-a}{\tau}})\, u(t-a) \right]$$

and the shapes of the responses are given below :

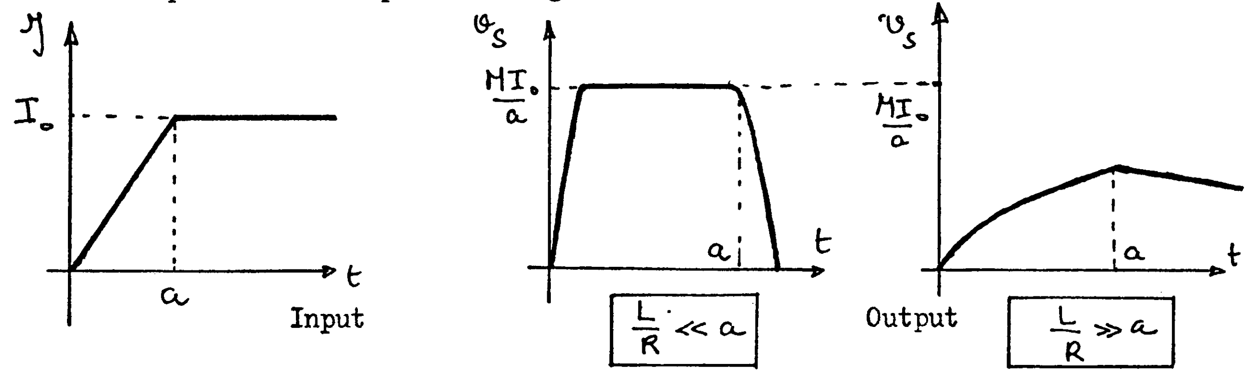


Fig.4 The pulse responses

We see that here also for $\frac{L}{R} \ll a$ we need an integrator and the response will be the following:

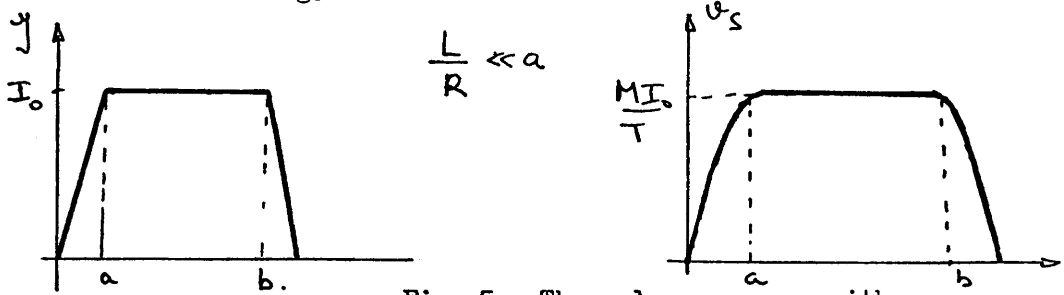


Fig. 5 The pulse response with an integrator.of time constant T

2.2. Capacitive Pick-up

We measure with this capacitive pick-up the electric-field produced by the internal conductor of the coaxial cable when the signal is applied and we shall see here what is the shape of the tension between the plate and the earth.

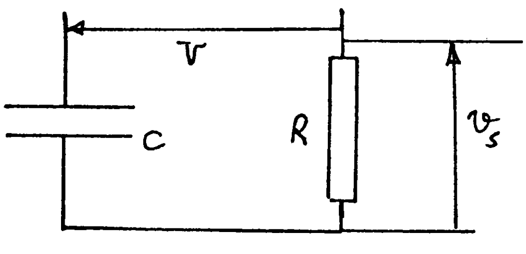


Fig. 6 The R-C circuit

We know that :

$$v_s(p) = V(p)\,\frac{\tau p}{1+\tau p} \qquad (1)$$

$$\text{with} \quad \tau = RC \qquad (2)$$

2.2.1. <u>Response to a square pulse signal</u>.

We have : $V(p) = V_0 \dfrac{1 - e^{-ap}}{p}$

$$v_s(t) = V_0 \left[e^{-\frac{t}{\tau}} u(t) - e^{-\frac{t-a}{\tau}} u(t-a) \right]$$

The following shapes are obtained :

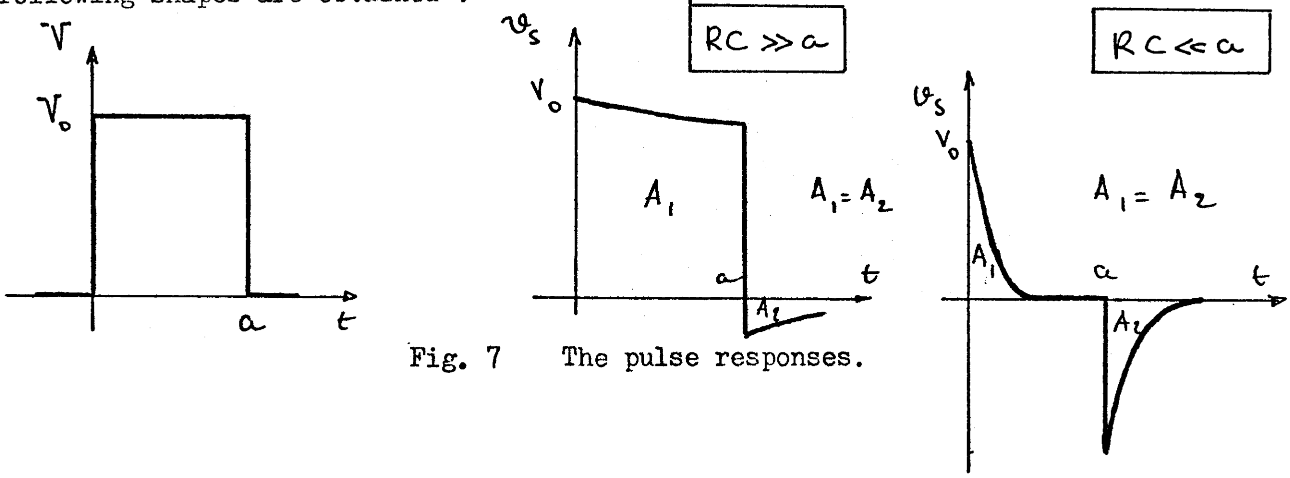


Fig. 7 The pulse responses.

Here also for RC $\ll a$ (or small τ) we need an integrator and we shall have the following response

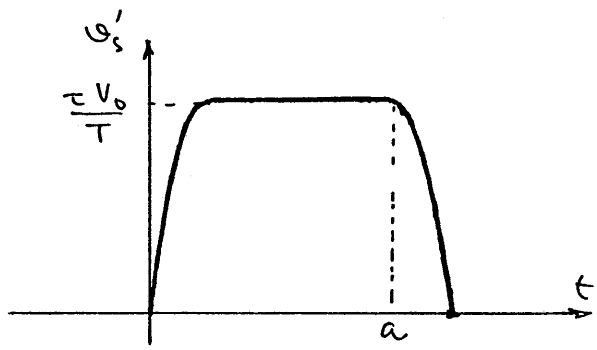


Fig. 8 The pulse response with an integrator of time constant T

We see here that this case is similar to the L-R study. It will be the same for the other shapes of pulse.

2.2.2 <u>Response to a pulse with a certain rise time a</u>

$$v = \frac{V_0}{a}\,\frac{1-e^{-ap}}{p^2} \qquad v_s(p) = \frac{V_0\tau}{a}\,\frac{1-e^{-ap}}{p(1+\tau p)}$$

$$v_s(t) = \frac{V_0\tau}{a}\left[\left(1-e^{-t/\tau}\right)u(t) - \left(1-e^{-\frac{t-a}{\tau}}\right)u(t-a)\right]$$

we obtain the following shapes of curves.

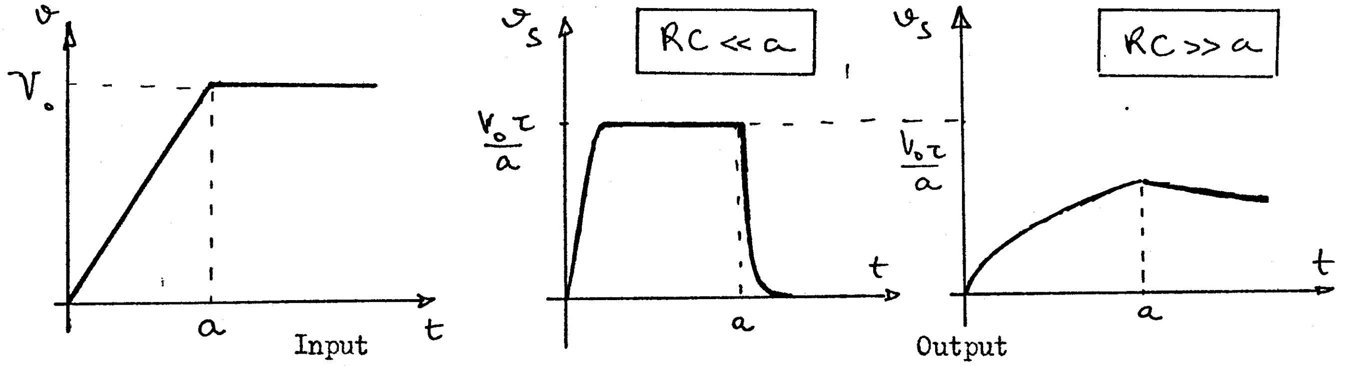


Fig. 9 Pulse responses

For the case RC << a we also need to integrate the signal.

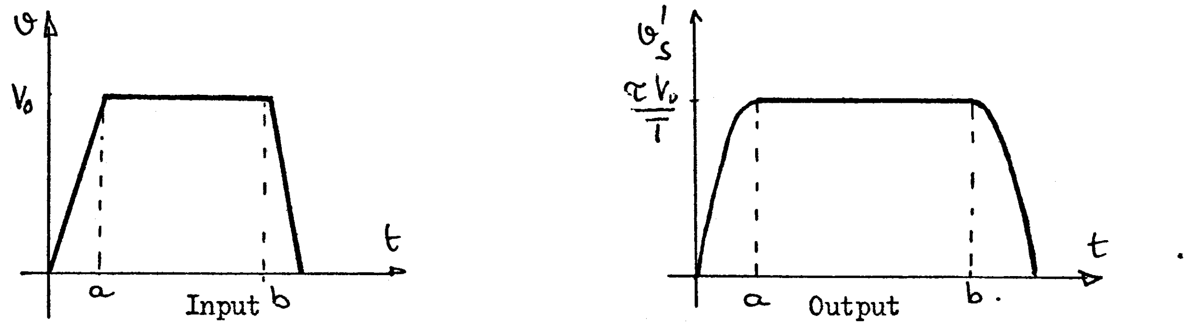


Fig. 10 Pulse response with an integrator.

In some cases we have a supplementary capacity to ground. So we have the following circuit which is more close to the reality.

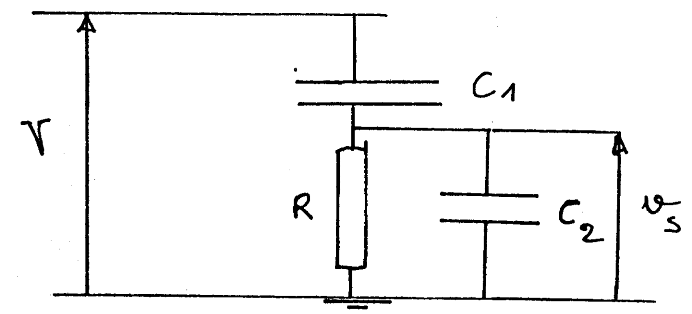


Fig. 11 The more real circuit

We now obtain for this case :

$$v_s(p) = V \frac{p\tau_1}{1 + p(\tau_1 + \tau_2)}$$

So in comparing with the other formulae p.4 (1)(2) we see that we have no change in the shapes of curves, but only in the amplitude.

We must multiply the amplitudes by a factor which is : $\tau_1 + \tau_2 / \tau_1$

2.3 Integrating inductive pick-up

It happens that the inductance does not behave always as a purely inductive one. There may be a capacity between the wires of the inductance or between the internal conductor of the coaxial cable and the inductance.

So if we assume that the first case can be neglected in first approximation; we have then the following equivalent scheme.

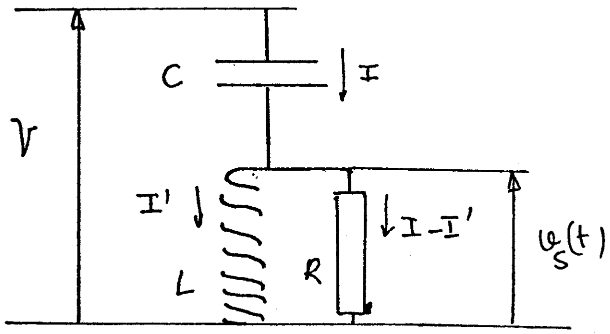


Fig. 12 The equivalent circuit

We have the following equations.

$$V = \frac{1}{Cp} I + R(I - I') \qquad e = -\frac{d\Phi}{dt} = -p\Phi = LpI' + R(I' - I)$$

then we deduce :

$$v_s(p) = \frac{p^2 \tau'^2 V + p\Phi}{1 + \tau p + \tau'^2 p^2} \quad \text{with} \quad \tau = \frac{L}{R} \qquad \tau' = \sqrt{LC}$$

$$\Phi = MJ \quad \text{and} \quad V = Z_L J$$

Here we assume also that the exchange of energy between the pick-up and the line can be neglected.

$$v_s = \frac{p^2 \tau'^2 Z_L + pM}{1 + \tau p + p^2 \tau'^2} J(p).$$

We apply here only a pulse with a certain rise time so :

$$\mathcal{J}(p) = \frac{I_0}{a} \frac{1 - e^{-ap}}{p^2}$$

and then we must discuss about two cases .

2-3-1 Case $\tau' < \frac{\tau}{2}$ or $\sqrt{LC} < \frac{L}{2R}$

$$v_s(t) = \frac{2 Z_L I_0 \tau'^2}{a\sqrt{\tau^2 - 4\tau'^2}} \Big[e^{-\frac{\tau}{2\tau'^2} t} \, sh \frac{\sqrt{\tau^2 - 4\tau'^2}}{2\tau'^2} t \,.\, u(t) - e^{-\frac{\tau}{2\tau'^2}(t-a)} \, sh \frac{\sqrt{\tau^2 - 4\tau'^2}}{2\tau'^2} (t-a) \,.\, u(t-a) \Big]$$

$$+ \frac{M I_0}{a} \Big\{ \Big[1 - e^{-\frac{\tau}{2\tau'^2} t} \Big(\frac{\tau}{\sqrt{\tau^2 - 4\tau'^2}} \, sh \frac{\sqrt{\tau^2 - 4\tau'^2}}{2\tau'^2} t + ch \frac{\sqrt{\tau^2 - 4\tau'^2}}{2\tau'^2} t \Big) \Big] u(t).$$

$$- \Big[1 - e^{-\frac{\tau}{2\tau'^2}(t-a)} \Big(\frac{\tau}{\sqrt{\tau^2 - 4\tau'^2}} \, sh \frac{\sqrt{\tau^2 - 4\tau'^2}}{2\tau'^2} (t-a) + ch \frac{\sqrt{\tau^2 - 4\tau'^2}}{2\tau'^2} (t-a) \Big) \Big] . u(t-a) \Big\}$$

So, here we have two cases

2-3-I-I τ' is very small

The first term can be neglected and the shapes of the curves are the following

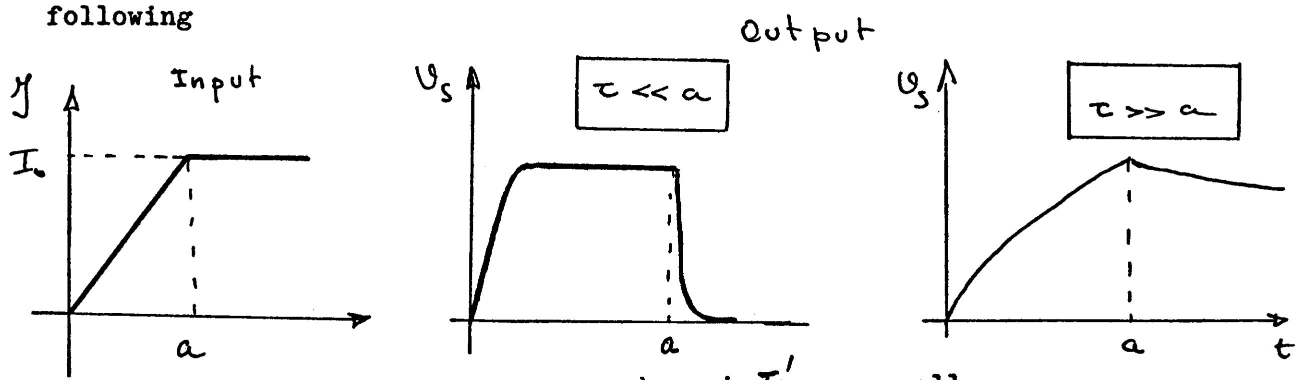


fig I3 Responses when is τ' very small

For the first case ($\tau \ll a$) we see that we need an integrator and then the signal is :

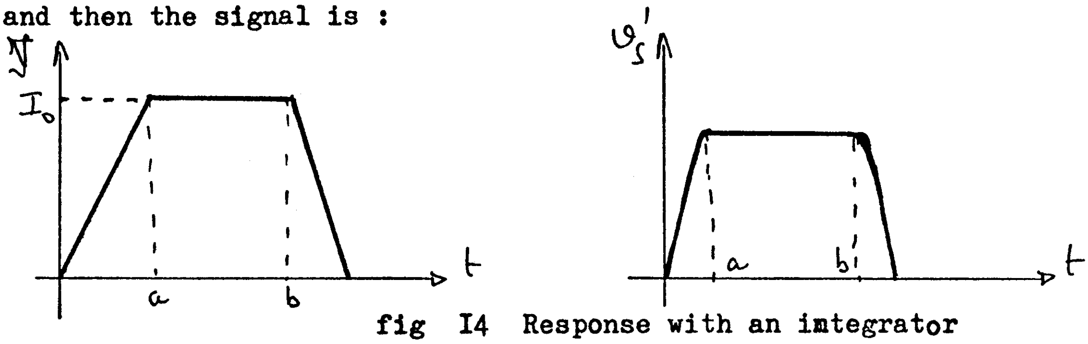


fig I4 Response with an integrator

2-3-I-2 The first term is no longer negligeable in front of the second one .

We shall not study this case because the value of τ' is such in this case that it never happems in reality .

2-3-2 Case $\tau' > \frac{\tau}{2}$ or $\sqrt{LC} > \frac{L}{2R}$

$$v_s(t) = \frac{2Z_L I_0 \tau'^2}{a\sqrt{4\tau'^2 - \tau^2}} \left[e^{-\frac{\tau}{2\tau'^2}t} \sin \frac{\sqrt{4\tau'^2 - \tau^2}}{2\tau'^2} t \; u(t) - e^{-\frac{\tau}{2\tau'^2}(t-a)} \sin \frac{\sqrt{4\tau'^2 - \tau^2}}{2\tau'^2}(t-a) \; u(t-a) \right]$$

$$+ \frac{MI_0}{a} \left\{ \left[1 - e^{-\frac{\tau}{2\tau'^2}t} \left(\frac{\tau}{\sqrt{4\tau'^2 - \tau^2}} \sin \frac{\sqrt{4\tau'^2 - \tau^2}}{2\tau'^2} t + \cos \frac{\sqrt{4\tau'^2 - \tau^2}}{2\tau'^2} t \right) \right] u(t) \right.$$

$$\left. - \left[1 - e^{-\frac{\tau}{2\tau'^2}(t-a)} \left(\frac{\tau}{\sqrt{4\tau'^2 - \tau^2}} \sin \frac{\sqrt{4\tau'^2 - \tau^2}}{2\tau'^2}(t-a) + \cos \frac{\sqrt{4\tau'^2 - \tau^2}}{2\tau'^2}(t-a) \right) \right] u(t-a) \right\}$$

This case ,also, is never found because the capacity C between the primary and the secondary circuit is not high enough.

This case shall give oscillations on the top of the pulse .

3. THE PICK-UP EXPERIMENTS

3.1 Low voltage experiments

The purpose of these experiments is to determine from what point of the circuit eventual reflections are coming and whether a mismatching should exist or not.

We charge here a cable which is 10 meters long and we discharge it by a Mercury switch into an end resistor through different kinds of devices.

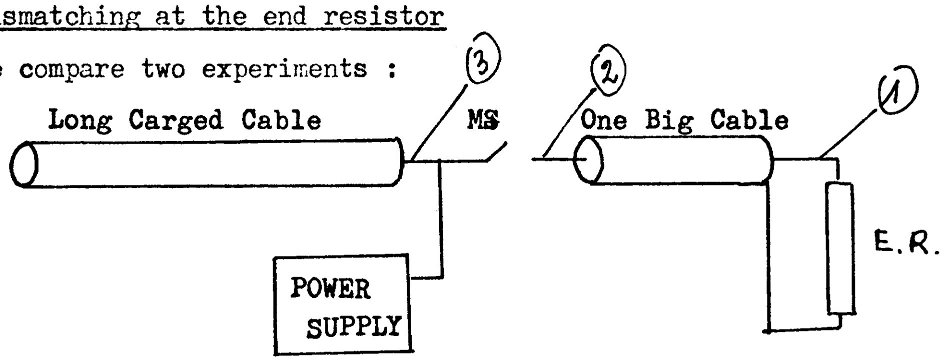
On the next pages, the different circuits are discribed.

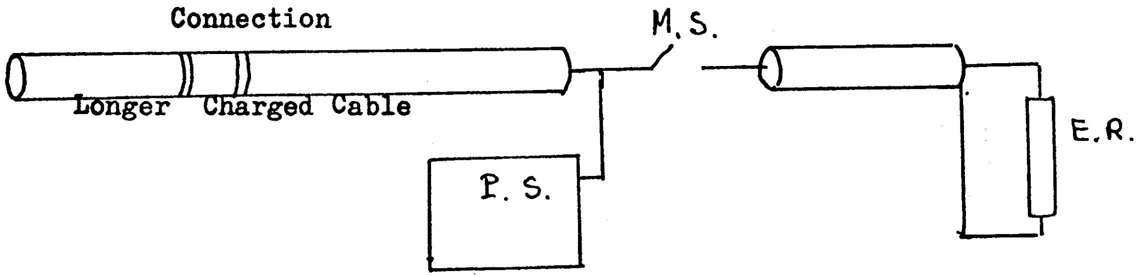
So,we measure the voltage with the scope in three different points, 1 , 2, 3, and we are able to see with these different experiments what are the effects of the introduction in the circuit of a spark gap (with the two electrodes touching each other) or of a connection between two big cables for example.

We deduce three peculiar properties of the circuit.

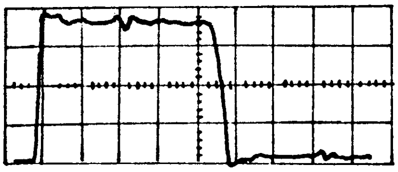
3.1.1 Mismatching at the end resistor

We compare two experiments :

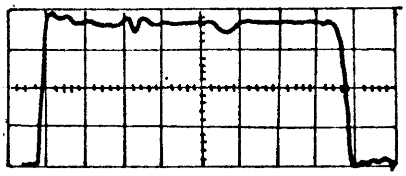




and then we obtain the two following pictures :



First experiments

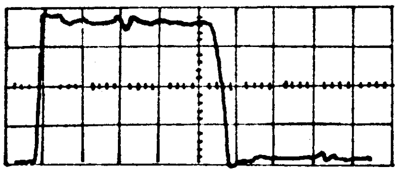


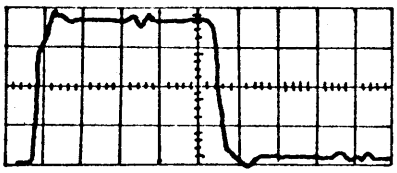
Second experiments with
a longer charging cable.

We measured the tension at the point 2. We see here clearly that the oscillations are coming from the end-resistor. The courbe determined by the place of the peaks on the top of the pulses. The second bump is coming from a mismatching at the connection between the two cables making the longer one.

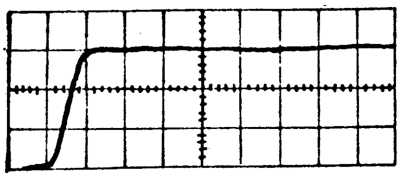
3.1.2 Effect of the spark gap

In comparing the pictures taken with circuit 1 and circuit 3 we saw the capacitive effect of the spark gap with his two electrodes touching each other.

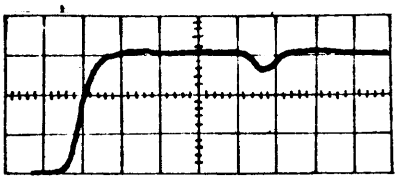




We know that in fact if we introduce in one part of a circuit a parasitic capacitor, we have the following effect :



Input



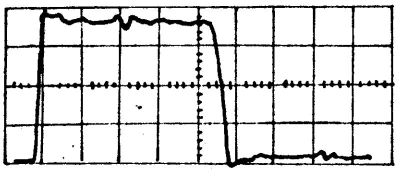
Output

It is exactly what is happening here at the beginning of the pulse.

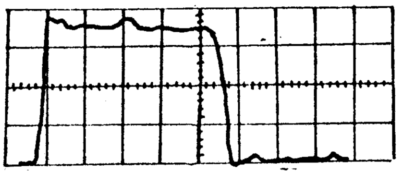
3.1.3 Effect of a connection between 2 big cables

In comparing the pictures obtained with circuit 1 and 2 or with circuit 3 and 4.

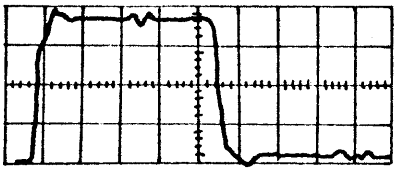
Circuit 1



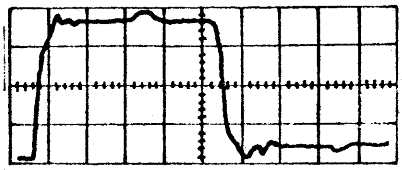
Circuit 2



Circuit 3

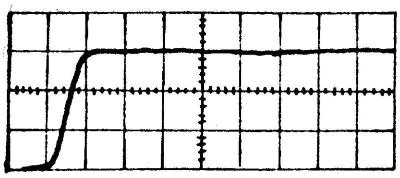


Circuit 4

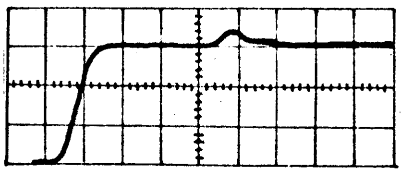


We see immediately that the only difference between the two couples of circuits was that instead of one cable put after the spark gap, we put two cables.

So, we can deduce that the effect of the connection is that of a parasitic small series inductor L. We know that in fact if we introduce in one part of our line a discontinuity which is here a small series inductance we have the following effect :



Input



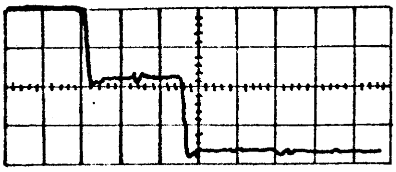
Output

Here we observe only a superposition of the two signals, but the conclusion remains the same.

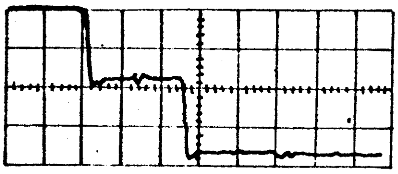
This effect disappears if we put instead of two big cables, only one very long thin cable.

All these effects, of course, can be seen at the measuring point 3.

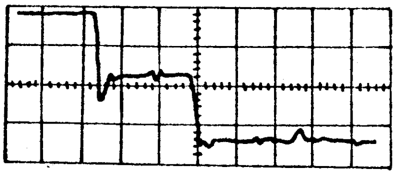
Effect of end resistor :



Effect of the spark gap :

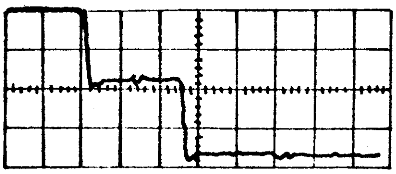


Circuit 1
without spark gap

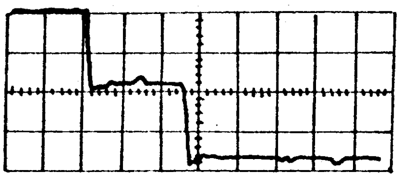


Circuit 3
with spark gap

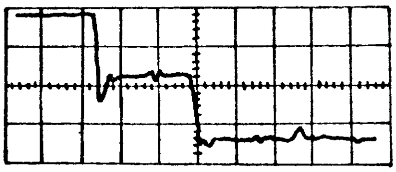
Effect of the connection between two cables :



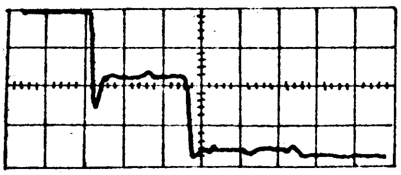
Circuit 1



Circuit 2



Circuit 3



Circuit 4

These shapes of the picture are normal because in this case we are before the Mercury switch ; so, the cable is charged, then discharged and we have half of the voltage. So there is a good matching of the cable.

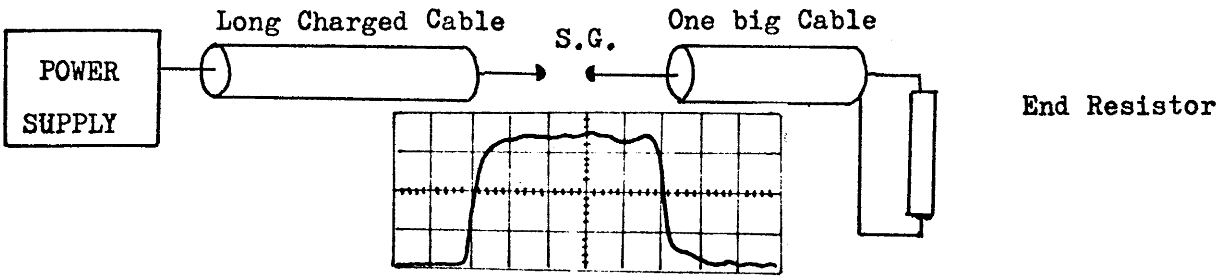
3-2 High voltage tests .

The purpose of these tests is to determine the response of the different pick-ups . We shall first test the circuit and after we shall look through the different pick-ups'responses.

3-2-I Tests of the circuit .

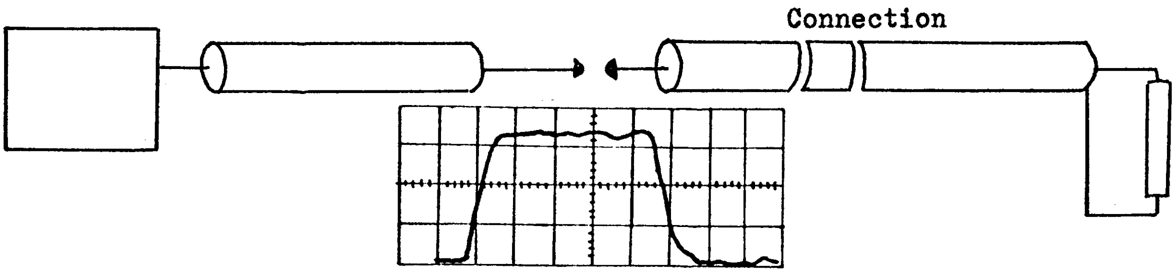
We made three circuits and we looked after the shapes of the pulse at the end resistor .

First Circuit



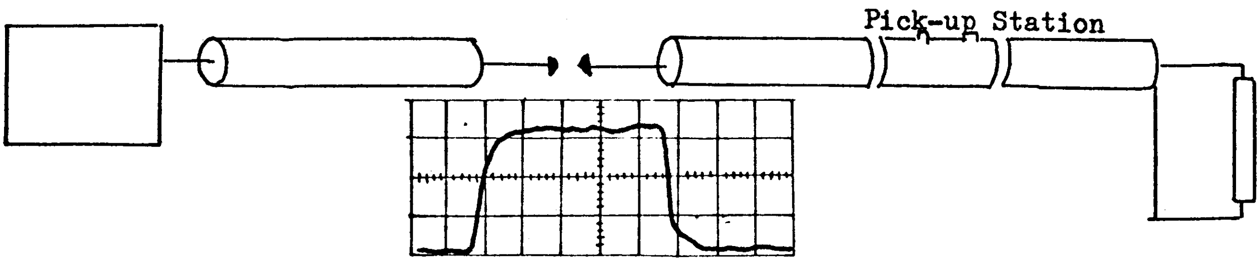
20 ns/cm

Second Circuit



20 ns/cm

Third Circuit



20 ns/cm

So we can see in comparing the different pictures that the reflection at the end resistor remains and that the pick-up station has a smaller effect on the top of the pulse than the effect produced by the connection between the two big cables .

3-2-2 Responses of the Pick-Ups .

We must take some cares for triggering because the trigger cable carries noise coming from the capacitive pick-up of the spark-gap.

The best solution is to put,at the end of the triggering cable, an integrator which divides also the voltage. Then,the oscillations will be damped .

3-2-2-I The Capacitive Pick-up (I)

We know for this pick-up that its equivalent scheme is the following :

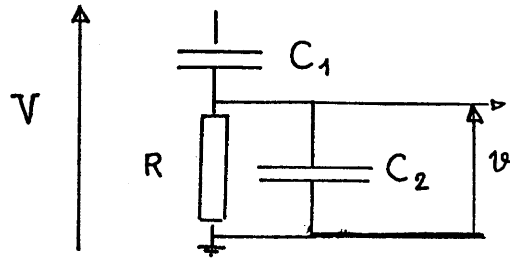
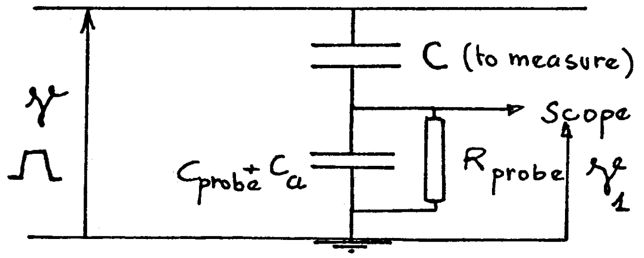
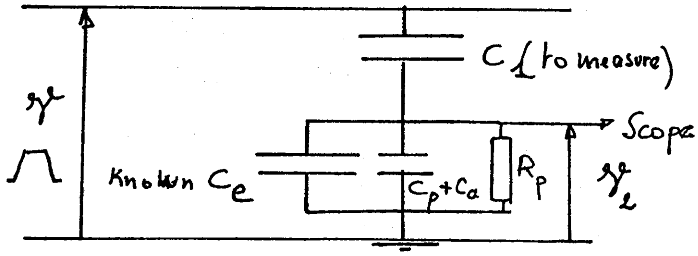


fig I4 : Equivalent Scheme

We measure the value of the capacity which exists between the internal conductor of the coaxial cable and the plate by using the two following circuits:





The value of the unknown capacity C is given by the formula:

$$C = C_e \frac{v_1 v_2}{(v_1 - v_2) v}$$

And here we found

$$C_1 = 9.2 \text{ pF}$$

Now we need the value of the pick-up's capacity which exists the plates and the earth+.This value should come out fromthe calculation of the amplitudes of the pulse.

We measure for the rise time of the pulse $a_{meas} = 10$ ns

But the real rise time is $a_{real} = \sqrt{a^2_{meas} - a^2_{Scope}} = 9.8$ ns

Then the time constant of the circuit is $\tau_1 = R\,C_1 = 0.46$ ns

and what we want to deduce know is the other time constant, $\tau_2 = R\,C_2$, which will be easily done because we know from the theoretical part that the amplitude of the pulse is given by :

$$v = V \frac{\tau_1 + \tau_2}{a_{real}}$$

and V is given by the amplitude of the pulse measured at the end resistor because we have there a divider of tension, so :

$$V = V_{mes} \times \frac{R_1}{R_2} = 6.4 \times \frac{50}{155 \times 10^{-3}} = 2\,060 \text{ V}$$

and ϑ is equal to $\vartheta = \vartheta_{measured} \times \frac{9.6 \times 10^{-6}}{9.8 \times 10^{-9}}$ because we put an integrator of 9.6 µs

Then we deduce $\tau_2 = 0.49$ ns

So the time constant of the circuit is $\tau = \tau_1 + \tau_2 = 0.95$.

Thus we are in the case given by the theory ($\tau \ll a$ fig. 7 and 8) and the theory and the experiments give the same results .

3-2-2-2 The inductive pick-up (2)

This pick-up is connected to earth, so we shall not have any capacity as in the previous case .

The value of the inductance is L = 0.25 µH

and the the value of the time constant is therefore L/R =5 ns

because we matched this pick-up directly to 50 Ω cable

The real rise time of the pulse is a = 9.8 ns

So we are in the case where L/R < a then the signal should be integrated and it is really what we have done+. The shape of the response is given in fig 3 : we obtain the same picture in our experiment.

3-2-2-3 The integrating inductive pick-up (3)

This pick- up was connected to earth first by the measuring cable and we were assuming that the equivalent scheme was given by fig I2

The inductance is made of many turns of copper wires on a ferrite ring. We started first with 4 windings and 7 windigs

We obtain for 7 windings L = 220 µH

we have R = 24 so the time constant is τ = L/R = 9.I5 µs

Then if we assume that the capacity between the internal conductor of the coaxial cable and the windinds of the inductance has a value inferior to C = 0.3 pF

we obtain for the other time constant $\tau' = \sqrt{LC} = 8$ ns

So we are really in the case where $\sqrt{LC} \ll L/2R$

and where $\tau \gg a$ because a = 9.8 ns , so the signal should not be integrated and it is what we observed.

But in increasing the number of windings , we obtained oscillations on the top of the pulse and after the pulse, that is to say that for a value of L= 740 µH and a value of the capacity C always very small , we were reaching the case $\sqrt{LC} \gtrsim L/2R$, which needs a capacity of the order of some nanofarads.

So we tried first to improve our equivalent scheme in putting a capacity in parallel with the resistance: this capacity isthe capacity which exists between the different wires of the inductance. But its value is still very small, and the theory was always in disagreement with the experiments. We tried also to see whether the exchange of energy between the line (or primary circuit) and the pick-up circuit was very great. But we found that this energy was very small, so it could not produce these oscillations.

Finally we found out that it was the earth ~~connections~~ loops which were giving theseoscillations, because in putting to earth only with the other end of the measuring cable, we were introducing a rather big inductance in our circuit, then we were able to have oscillations.

So we soldered one wire of the inductance to the housing of the pick-ups and then we have the picture given in Annex 2 .

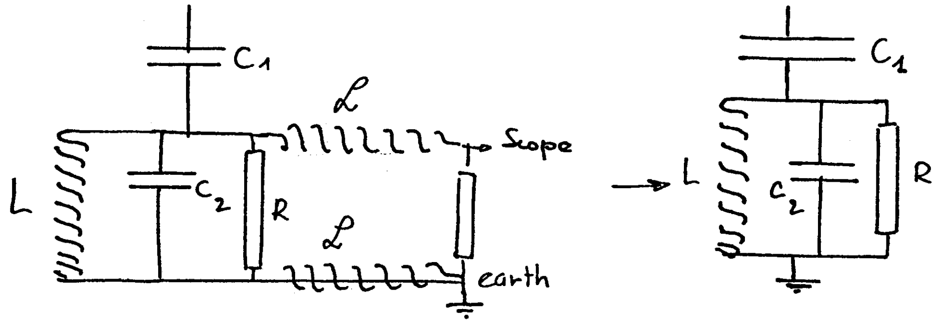


fig I5 The improvements of the circuit

We can see on the picture that it still remains a bump at the beginning of the pulse, it could be eliminated if a modification of the housing of the pick-up might be possible,which is not the case .

3-3 Comparison of some pick-ups .

The use of an integrator is in some cases not very convenient so, it is the integrating inductive pick-up which is more useful

Nethertheless we can have a good response with the other pick-ups . We used also an other inductive pick-up without the earth - connections and we had the same problems as in the previous case,but here we were in the case of fig I4 and we needed an integrator.

We can say also that the shapes of the pulse obtained for the integrating inductive pick-up without earth connections and with a low number of windings are very good but the determination of the amplitude of the pulse is not easy .

4 . Conclusion .

In these experiments we have seen that there is no disagreement between the theoretical point of view and the experiments.

Some improvements on the integrating inductive pick-up can be made in order to have a better translation of the pulse.

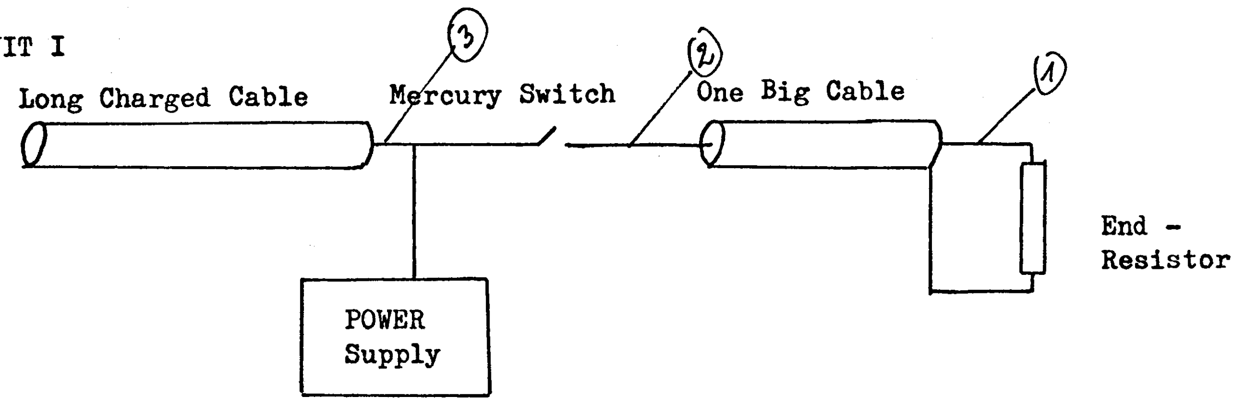
Acknowledgements

I must thank Mr.H.RIEGE who gave to me the basic ideas which have lead to the edification of this report.

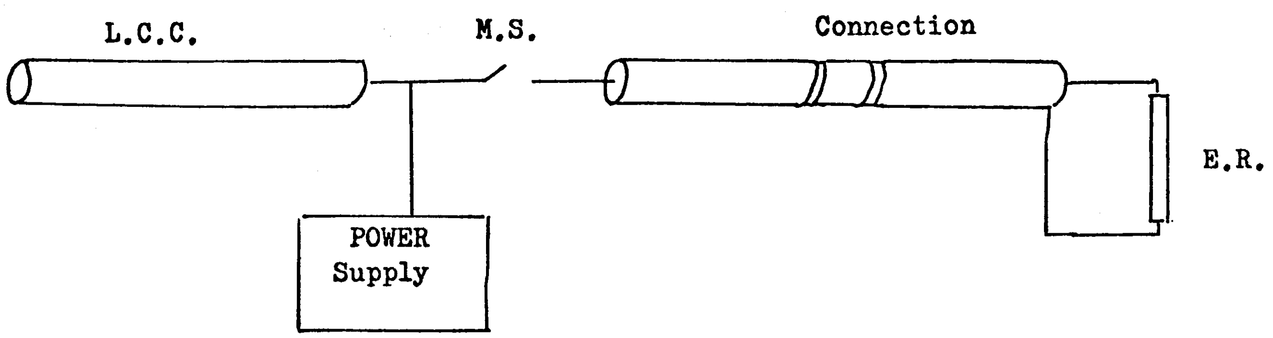
ANNEX I

LOW VOLTAGE CIRCUITS

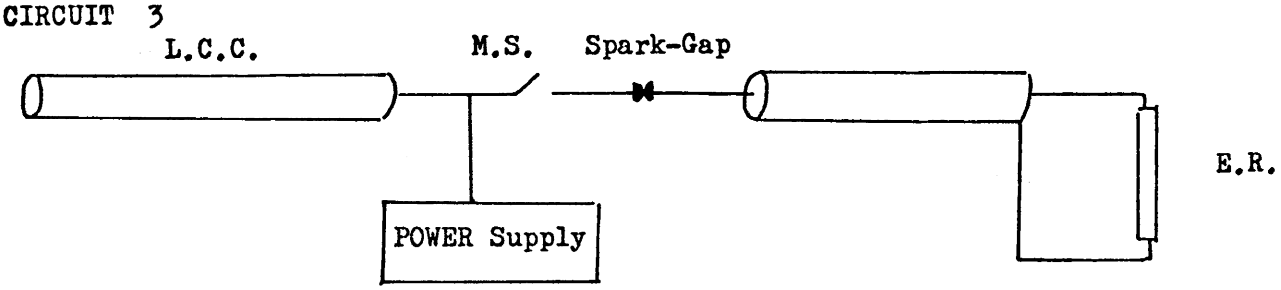
CIRCUIT I



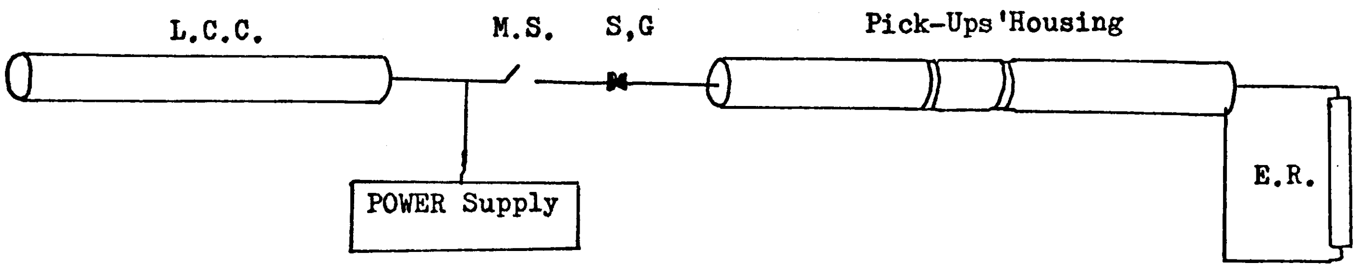
CIRCUIT 2



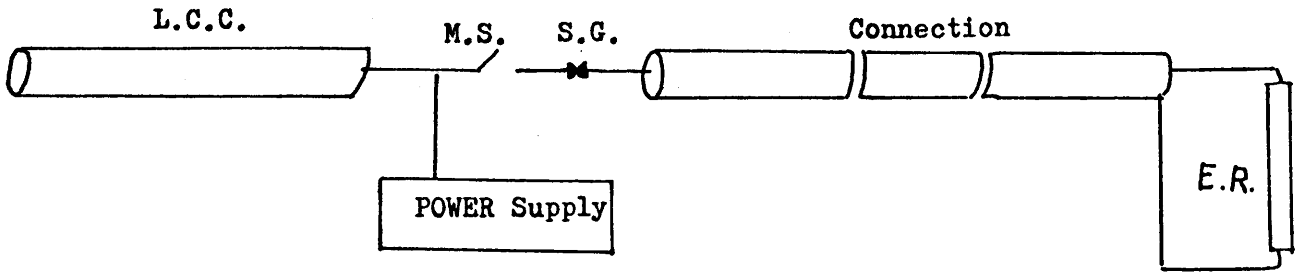
CIRCUIT 3



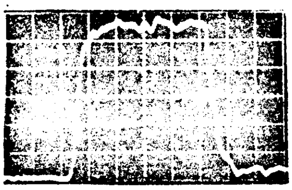
CIRCUIT 5



CIRCUIT 4



END-RESISTOR PICK-UP

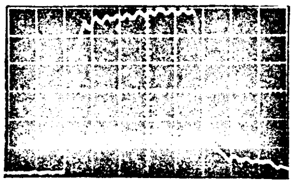


20 ns/cm

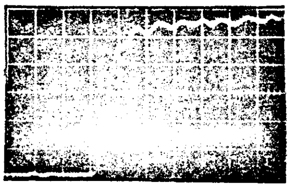
10 ns/cm

without integrator

CAPACITIVE PICK-UP



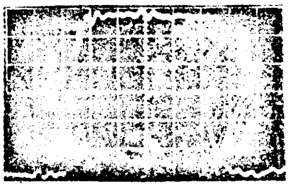
20 ns/cm



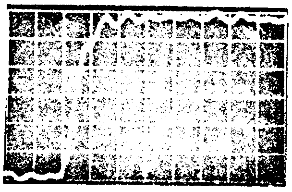
10 ns/cm

with integrator

INDUCTIVE PICK-UP WITH EARTH CONNECTIONS



20 ns/cm



10 ns/cm

with integrator

INTEGRATING INDUCTIVE PICK-UP

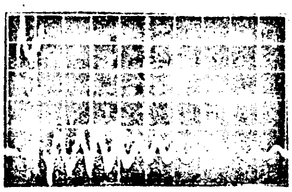
4 windings

20 ns /cm

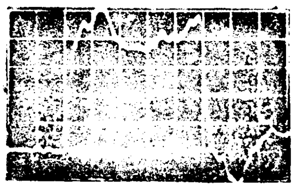
10 ns/cm

without integrator and without earth connections

40 windings

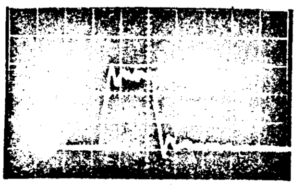


100 ns/cm

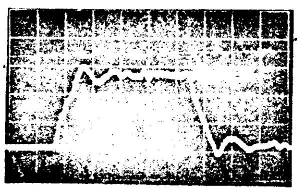


20 ns/cm

30 windings

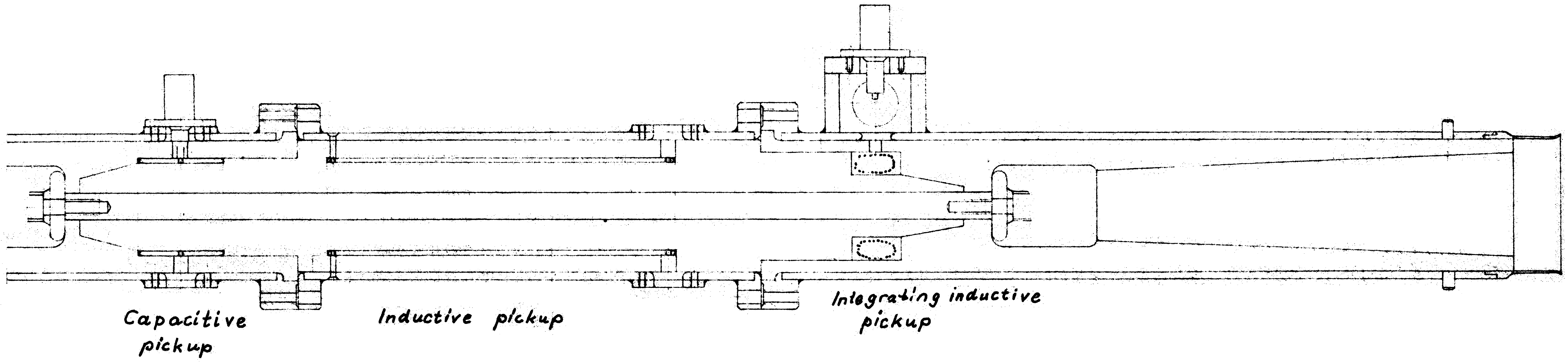


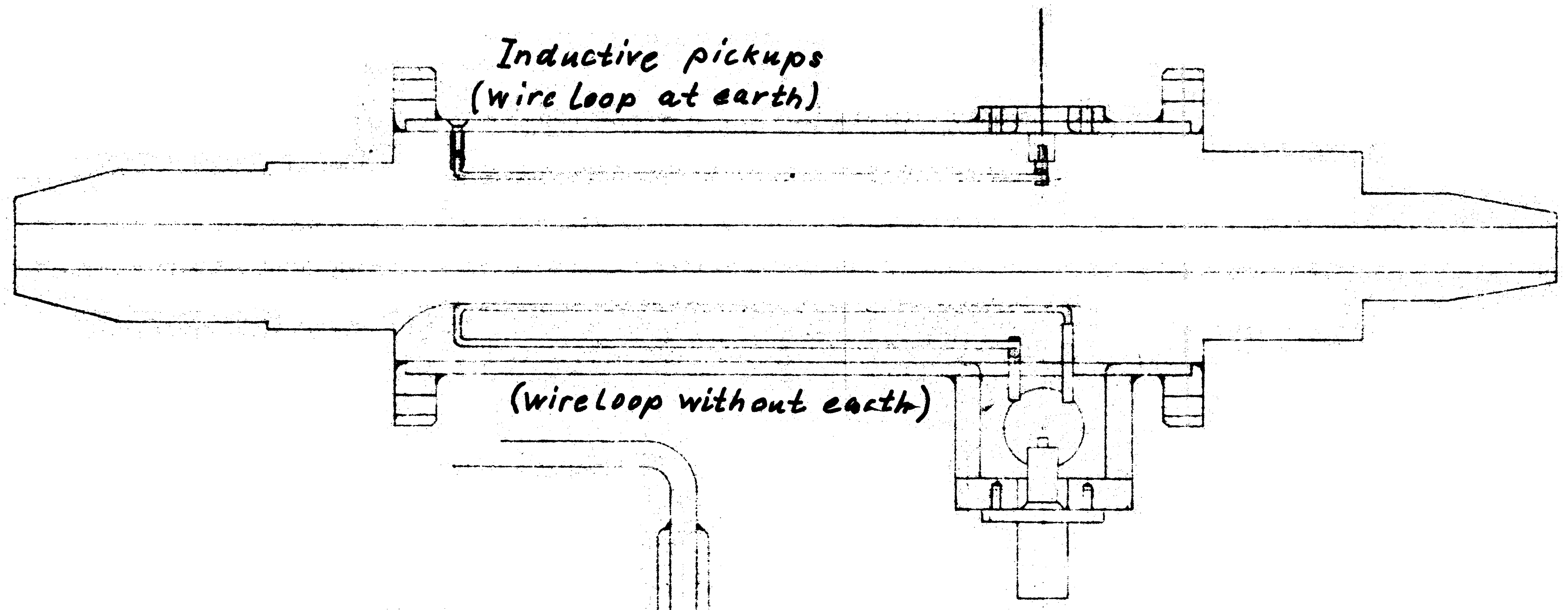
50 ns/cm

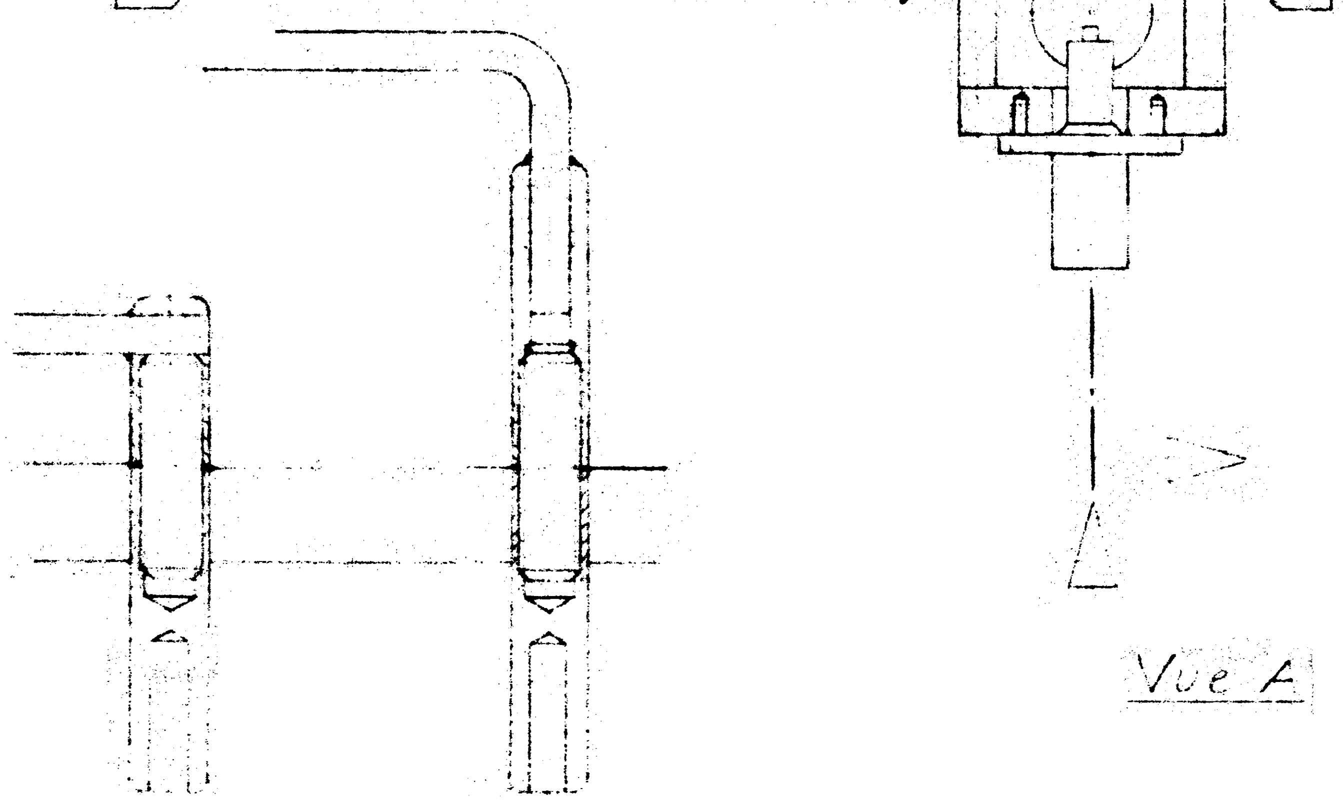


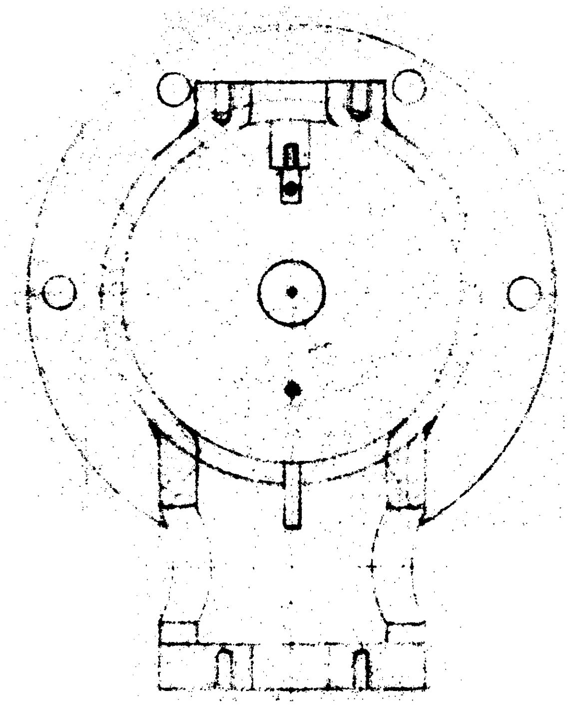
20 ns/cm

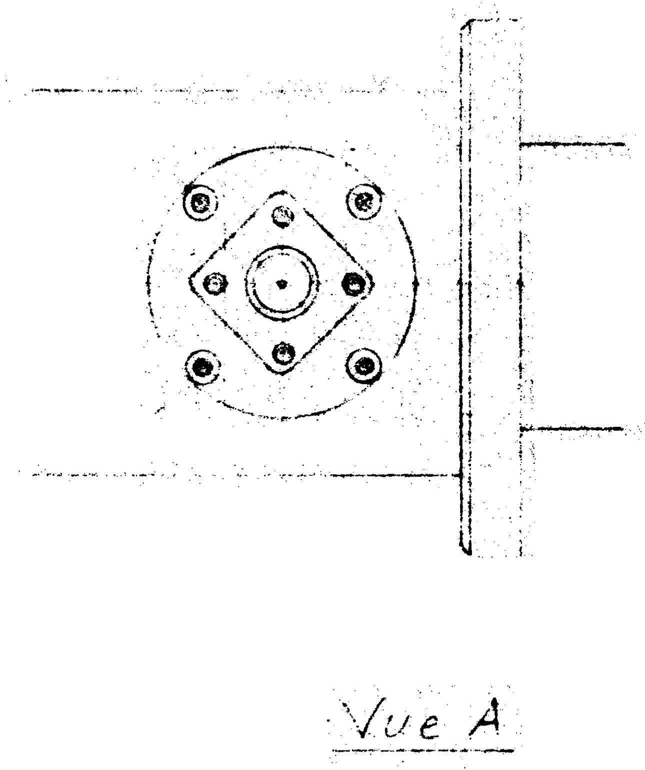
with earth connections











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III	II	I				

Mod.	Date	Nom	Tolérances générales		
A			de	à	±
B			de	à	±
C			de	à	±

Ensemble — S. Ensemble — Echelle

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Contrôlé
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Pickup housing

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