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PROJECT :

TURBULENCE EXPERIMENT IN THE AFTERGLOW PLASMA

Power Pulse Generators Requirements and Measurement Feasibility

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I. INTRODUCTION

The plasma box NESSIE is presently working as a DC experiment and some parameters have still to be investigated in this state (T_e/T_i, fluctuation level, turbulent spectrum, drift velocity of the electrons). However, some new information (e.g. the current in the plasma) and a deeper insight of the turbulence mechanism could be drawn from a pulsed experiment. This requires a complete change in the diagnostics methods; the main power supplies for producing the plasma and for applying the potential between cathode and anode have to be reconsidered. A time sequence must be worked out.

In this report, we want to present the planned power supplies and the switching circuits. The main measurements we shall have to perform are discussed in section V.

II. WORKING SCHEME

The 3m-tube carries 600 permanent magnets on its external surface. It is cooled by water flowing inside four hollowed longitudinal bars. At both ends of the tube, a hot 'cathode' is heated by continuous electron bombardment (filament heating : $\sim$ 30 V, 12 A; acceleration voltage between plate and filament : $\sim$ 2 kV, 250 mA. Total power : $\sim$ 850 - 900 W). The plasma is produced by the 8 Tungstene filaments, which are kept at high temperature ($\sim 2000^{\circ}$C) by a DC power supply (40V, .8 A). The biasing voltage (-40V to -60V) applied to the filaments has to be replaced by a pulsed power supply delivering 0 to -60V, 1A with a pulse width of 1 to 10 ms.

The plasma turbulence should be obtained by drawing a current between cathode and anode, in the afterglow plasma. The pulsed power supply needed for biasing the cathode must give a voltage of about -100 V, for a pulse width of about 100 μs. The needed current can be estimated:

$$i = nevA = 10^{10}_{[cm^{-3}]} \times 1.6 \times 10^{-19}_{[cb]} \times 8 \times 10^{7}_{[cm/s]} \times \frac{\pi}{4} \times 10^{2}_{[cm^2]} \simeq 10\,A$$

with $n = 10^{10} cm^{-3}$, the radius of the cathode = 10 cm and $T_{e_{max}}$ = 4eV.

The pulses can be produced by the use of thyristors DC static switches. The use of fast switching transistors has been excluded because our experimental conditions are out of their safe operating area.

In order to minimize the leakage current to the wall, a current of about 1kA is continuously drawn on the tube (voltage between both ends of the tube : 2.8 V to 3.0 V).

III. TIME SEQUENCE

a) Plasma production : the plasma will be produced by biasing the 8 Tungstene-filaments at -40V to -60V ($\sim$.5 A) during a few milli-seconds. The power supply should be floating in order to use a classical regulator circuit.

Timing :

Biasing voltage pulse	:	1 - 10 ms
Afterglow (estimated)	:	$\sim$1 ms - 2 ms
Repetition rate	:	3 - 20 ms

b) Current in the plasma : the current in the plasma will flow between the cathode and the anode. A negative pulse of 0 V to -100 V will be applied to the cathode, the anode being grounded. Here too, the power supply must be floating.

Timing :

Applied voltage pulse	:	100 μs
Switching-on	:	.05 - .1 ms after the beginning of the afterglow
Repetition rate	:	3 - 20 ms

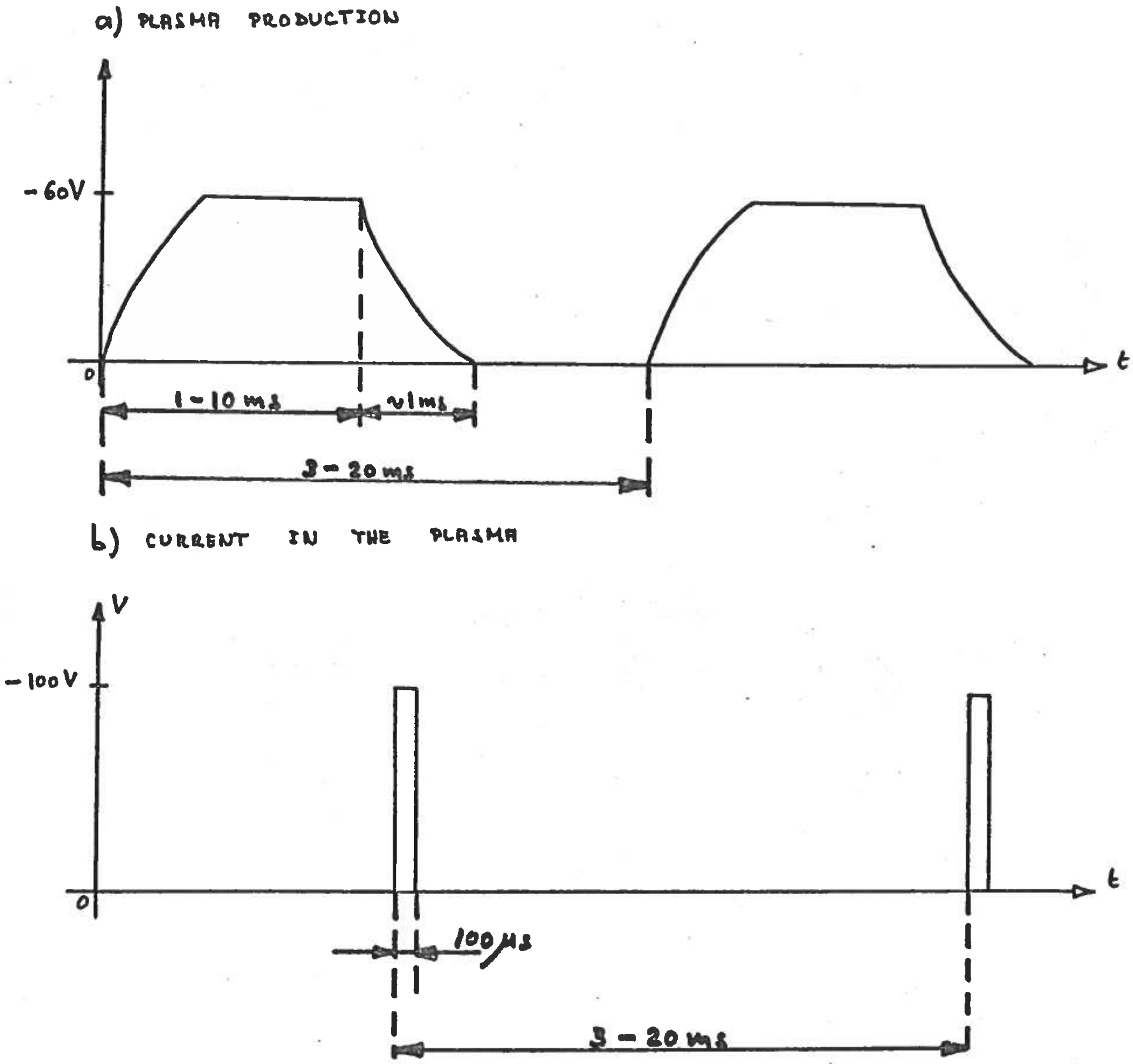


Fig. 1

IV TECHNICAL DATA

The NESSIE experiment is already fitted out with some instruments and supplies which we can use in the pulsed stage : They are listed here :

Spectrum Analyzer 7L12 : Lower sweep rate ≃ 20 s. for total sweep. External trigger on left plug-in vertical time base 7B50

DC Power Supply E/M (SCR) : 40 V - 150 A (Filament heating)

DC Power Supply 6kV - 1A : } cathodes heating
2 x Power Supply 60V - 15A: }

Scope 7603 TEXTRONIX

Pulse generators available :

PHILIPS 5715 : 1 Hz - 50 MHz

2 x EXACT : .01 Hz - 10 MHz

However, the main power supplies and the switching circuits must be built.

Power Pulse Generators Requirements

a) Power Supply 60V, 1A (see Fig. 2)

Transformer P. 220 V - S. 60V, 1A/25V, .05A : ordered to MAPROMAT.
Delivery time : end of August

Rectifier bridge : ordered to MOTOROLA
delivery time : -

Transistors : MJE 340 and MJ 15003 : ordered to MOTOROLA
delivery time : -

Requirements : The power transistors must deliver 1A under 60V. A MC 1466 L will be used as a current regulator on the amplifier circuit. At the first stage, we shall use a MJE 340. Two MJ 15003s will certainly be used for the current supply. The cooling of the transistors will be done by metallic coolers (FABRIMEX).

b) Power Supply 100V, 10A (see Fig. 3)

Transformer P. 220 V - S. 100V, 10A/25V, .05A : ordered to MAPROMAT.
Delivery time : end of August

Rectifier bridge : BYW 20. Ordered to MOTOROLA
Delivery time : -

Requirements : The power transistors must deliver 1A under 100V. A MC 1466 L will be used as a current regulator on the amplifier circuit. At the first stage, one MJE 340 will be used. For the current supply, it will be necessary to have about 20 MJ 15003s so that each transistor works in its 50A (safe operating area). The cooling of the transistors will be performed by metallic coolers and fans.

OPTION :

The number of MJ 15003s can be drastically reduced by introducing a thyristor safety circuit at the output of the power supply (see fig. 4). The feedback on the gate of the thyristor in case of short-circuit will limit the current through the transistors. The power dissipation in the transistors should be lower in case of short-circuit than in case of working state.

Dissipated power on one MJ 15003 transistor :

- working state : about 30V, 10 A (~300 W)
- short-circuit : about 100 V, 1A (~100 W)

The first tests of this option show a good behaviour of the system.

c) Switching Circuits (see Fig. 5)

We present here two ways of making a switching circuit. A choice will be made after having tested the performances of each one.

A system with fast switching transistors has been considered. But our requirements are out of the 50A and this option has been given up.

Comments on the circuit Fig. 5.a)

The elements ZD, C3, Q1 and Q4 drive the gate of Q2 which switches on. When the contral signal is removed, Q1 and Q4 turn off. This removes the gate drive on Q2 and provides a gate drive on Q3 which commutates Q2 off.

Choice of the elements

Power Supply 60V, 1A	Power Supply 100V, 10A
Q2 : 2N4178 (200V, 8A)	2N6158 (400V, 30A)
Q3 : 2N 1597 (200V, 1.6A)	2N 4172 (400V, 8A)
Q4 : MCR 104 (100V, .8A)	MCR 106-4 (200V, 4A)

The other elements must be adjusted with the amplitude of the central signal.

Comments on the circuit Fig. 5.b)

T1 switches on and gives the voltage to the load. When T3 switches on, C2 begins loading and C1 commutates T1 off. The current through T3 stops when C2 is loaded. C2 is unloaded through T2.

Choice of the elements:

	Power Supply 60, 1A	Power Supply 100V, 10A
T1	: MCR 106-3 (100V, 4A)	2N6402 (200V, 16A)
T2&T3	: MCR 104 (100V, .8A)	MCR 106-4 (200V, 4A)

The other elements must obey the following relations :

$$C2 = 2.72\ C1$$
$$C1 \geqslant t_q / R_{load}$$
$$L \geqslant 20\ R_{Load} \cdot t_q$$

where $R_{load} = \frac{V_{applied}}{I_{load}}$ and t_q is the recovery time of the thyristor T1.

OPTION:

The switching mode could be undertaken by using a PNP Darlington (transistor DC static switch) on the negative output of the regulated source.

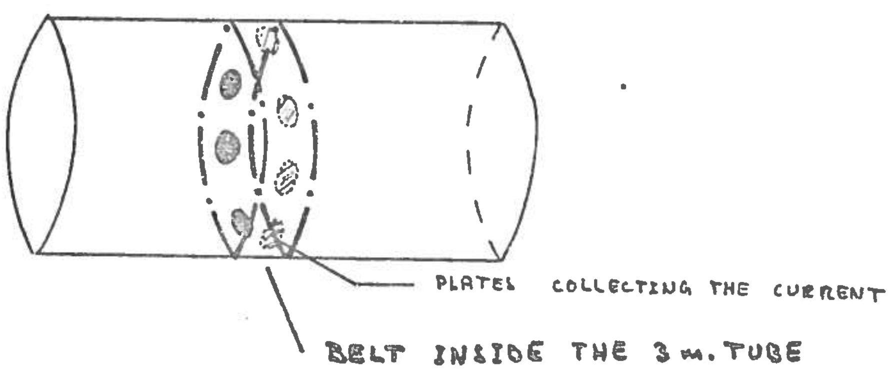
V. MEASUREMENTS FEASIBILITY

1. Steady State Experiment

- Measurements of the electron drift velocity using ion acoustic test waves are under processing. This method requires the measurements of the wavelength in both Z-directions.
- Measurements of the temperature ratios T_e/T_i using ion acoustic test waves are under processing. This method requires a comparison between the theoretical dispersion relation (calculated for different T_e/T_i) and the experimental one.
- Measurements of the turbulent spectra with the cross correlator (100 kHz - 1.2 MHz). This should show us that the turbulent frequencies belong to the ion acoustic dispersion relation.

2. Pulsed State Experiment

- Measurements of the density with a Langmuir probe.
- Measurements of the current flowing in the plasma with Rogowski coils inside the tube.
- Measurements of the leakage current to the wall at different points along the tube. This requires the construction of belts with small metallic plates which catch the leakage current.



- Measurements of the electron distribution function with the particles (or energy) analyzer.
- Measurements of the turbulent spectra with the spectrum analyzer.

In most of these measurements we may have to use a BOXCAR Integrator (PAR, Model 162) either as a sampling tool or with a digital option. We give here some useful characteristics of the instrument :

Aperture duration : 5 ns - 5 ms

Average : exponential

Minimum repetition rate : $\frac{2 \cdot 10^{-5}}{\text{Aperture Duration}}$ for aperture duration $\leqslant 5\mu s$

$\frac{2 \cdot 10^{-7}}{\text{Aperture Duration}}$ for aperture duration $> 5\mu s$

In our case, the signal duration is $100\mu s$. The more points we have during this time, the better the results. If we take an aperture duration of 5ns, the minimum repetition rate (for 1% full scale error) is 4 kHz and with 50 ns aperture duration, 400 Hz. The former case implies a repetition time smaller than .25 ms and the latter case, smaller than 2.5 ms. We see that in order to avoid a big error, we must choose a very small repetition time. But there is another limit : before switching off the plasma production, we must be sure that the plasma is established. The confinement time gives an estimation of the time needed to create the plasma.

Neglecting all electric effects, we can calculate the time constant if we assume that the plasma is leaking out through the open surface of the cusps. According to Berkowitz and al. and Grossmann, the open diameter of a cusp is of the order of the ion cyclotron radius :

$$S = \pi \left(\frac{M_i V_{Ti}}{e B} \right)^2$$

The confinement time is defined by :

$$\tau = \frac{V}{v_{T_i} \cdot S} = \frac{V\,(eB)^2}{\sqrt{27} \cdot \pi \cdot N \cdot M_i^{1/2} \cdot (k_B T_i)^{3/2}}$$

where V is the volume of the box and N the number of cusps. For NESSIE, $V = .13\ m^3$, $B \cong 1.2$ kG, $M_i = 40 \cdot m_p$, $N \simeq 600$, $k_B T_i \simeq .2$ eV. With these values, τ is of the order of 2 ms !

The shorter repetition time we can have will be of the order of 4 ms. In this case, the error will be larger than 1% full scale. If we choose an aperture duration equal to 50 ns, we estimate the error to ~5% full scale.

In summary, we are limited by the repetition time of the pulse and by the repetition rate of the BOXCAR integrator. In our case, with a signal of 100 μs, the optimum is :

- aperture duration (BOXCAR Gate) : 50 ns
- repetition time of the pulse : 4 ms
- number of points in 100 μs : 2000 points

Measurement procedure

A complete block diagram showing the measurement facility is presented in Fig. 6.

a) Langmuir probe (see Fig. 7)

A rough estimation of the density will be performed using a calibrated Langmuir probe, continuously biased at the ion saturation potential. This should give even an idea of the discharge pulse to check a possible increase in density during the 100 μs current pulse.

b) Rogowski coil (see Fig. 8)

In order to measure the net current flowing in the plasma, four large Rogowski coils will be placed inside the 3m-tube.

Characteristics of the coils :

- Shape : torus
- n = 1680 - 1710 turns
- large diameter : R = 20.0 ± .3 cm
- small diameter : a = 1.0 ± .1 cm
- theoretical inductance : ~ 10 H
- measured inductance : ~ 470 H (⇒ R = .8 Ω for a rep.time of 4 ms)
- measured voltage at the output of the coil with 1A and 10A through the coil, integration time τ = 10 ms :

$$U = \frac{1}{\tau} \int_0^t \frac{d\phi}{dt}\, dt = K \cdot I = \frac{\mu_0 a^2 n}{2 R \tau} \cdot I = \begin{cases} 50\,\mu A \\ 500\,\mu A \end{cases}$$

The signal will be averaged by the BOXCAR with an aperture duration of 50ns.

With a fixed gate on the BOXCAR, we shall be able to measure the mean current in the plasma at a fixed time in the 100μs pulse. For an integration time of 10 ms the measurement will take 800s (13'20") and include 200'000 points. If we assume a good reproducibility of the discharge and then a good correlation between the pulses, we can study the current evolution during the 100 s. This requires to make the gate of the BOXCAR slowly sweeping.

c) Energy Analyzer (see Fig. 9 and 10)

The particles analyzer will be used, first, as a Langmuir probe (Fig. 9). A slow sawtooth will be applied to the grid and the BOXCAR integrator will be used in sampling mode to measure the Langmuir characteristics I(V). With a sweeping time of 100s for the sawtooth (EXACT or PHILIPS generator) and an aperture duration of 50ns, we can measure about 25'000 points if the discharge repetition time = 4 ms.

Then, the particle analyzer will be used as an energy analyzer (Fig. 10). This method requires the use of a LOCK-IN amplifier. An oscillating signal (frequency ≃ 5 kHz) is added on the slow sawtooth applied to the grid. The signal picked up on the collector with the BOXCAR is sent to the LOCK-IN and compared with the reference. At the output of the LOCK-IN, we have $f_e(V) \sim \frac{dI}{dV}$.

d) Spectrum Analyzer

The measurement of the turbulent spectrum can be done by two different ways :

1. Spectrum analyzer with a sawtooth driving the frequency sweep. The measurement is made at a fixed point on the 100μs pulse. The BOXCAR is used as a sampling-and-hold tool. This way, we get the amplitude of the turbulent spectrum as a function of the frequency. However, no information about the time evolution of the spectra are available by this method. It should be noted that with the digital option of the BOXCAR, the overall hold time can be increased up to 300 s.

2. Transient Recorder. This instrument converts analog signals into digital data and stores the information in a digital memory. The considered transient recorders have a frequency response from 25kHz to 25 MHz and a typical memory length of 2000 words. The typical time of measurement is of 10 ms per point in the fastest case (BIOMATION 8100). In our experiment, it would be useful to measure the turbulent signal with 2000 points in 100μs (or less, if we want to increase the time resolution). The stored data would be introduced into a code performing a Fourier analysis in order to get the frequency spectrum. The main problem is the time needed to discharge the memory : this time depends mainly on the interface. The limitation on the transient recorder is a minimum discharge time of about 200 ms with a recovering time of 500μs between the last recalled point and the first recorded one. This means that with a repetition time of say 4ms in the pulses, only each 50th pulse could be measured.

The fastest system could be reached by using a minicomputer at the interface. However, the cost of such an instrumentation may be a big handicap to its purchase.

FIGURE CAPTIONS

Figure 2 : Scheme of the 60 V, 1A power supply

Figure 3 : Scheme of the 100V, 10A power supply

Figure 4 : Option for the 100V, 10A power supply. A thyristor safety circuit is used to limit the power dissipation in each power transistor in case of external short-circuits.

Figure 5 : Thyristors DC Static Switches. Two options are presented.

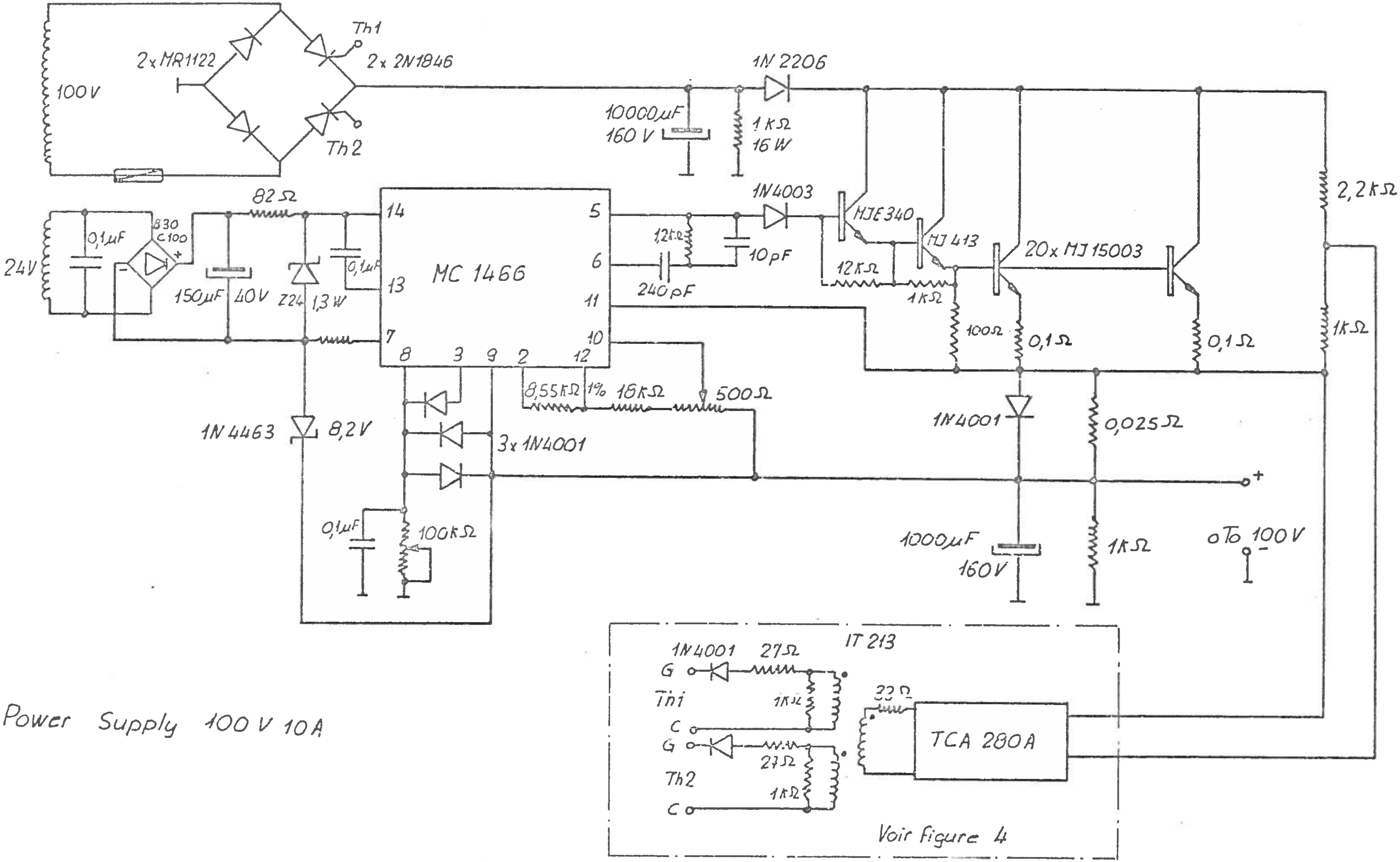
Figure 6 : Complete block diagram of the experiment. The repetition time has been chosen equal to 6 ms (plasma production during 3 ms). The delay line is needed to have the 100μs pulse during the afterglow.

Figure 7 : Block diagram of the Langmuir probe circuit.

Figure 8 : Block diagram of the Rogowski coil circuit.

Figure 9 : Block diagram of the particles analyzer circuit. With such a scheme, we get the characteristic I(V).

Figure 10 : Block diagram of the particles analyzer circuit. With such a scheme, we get the distribution function $f(E) \sim dI/dV$.



Power Supply 100 V 10 A

Fig. 2

Power Supply 60 V 1A

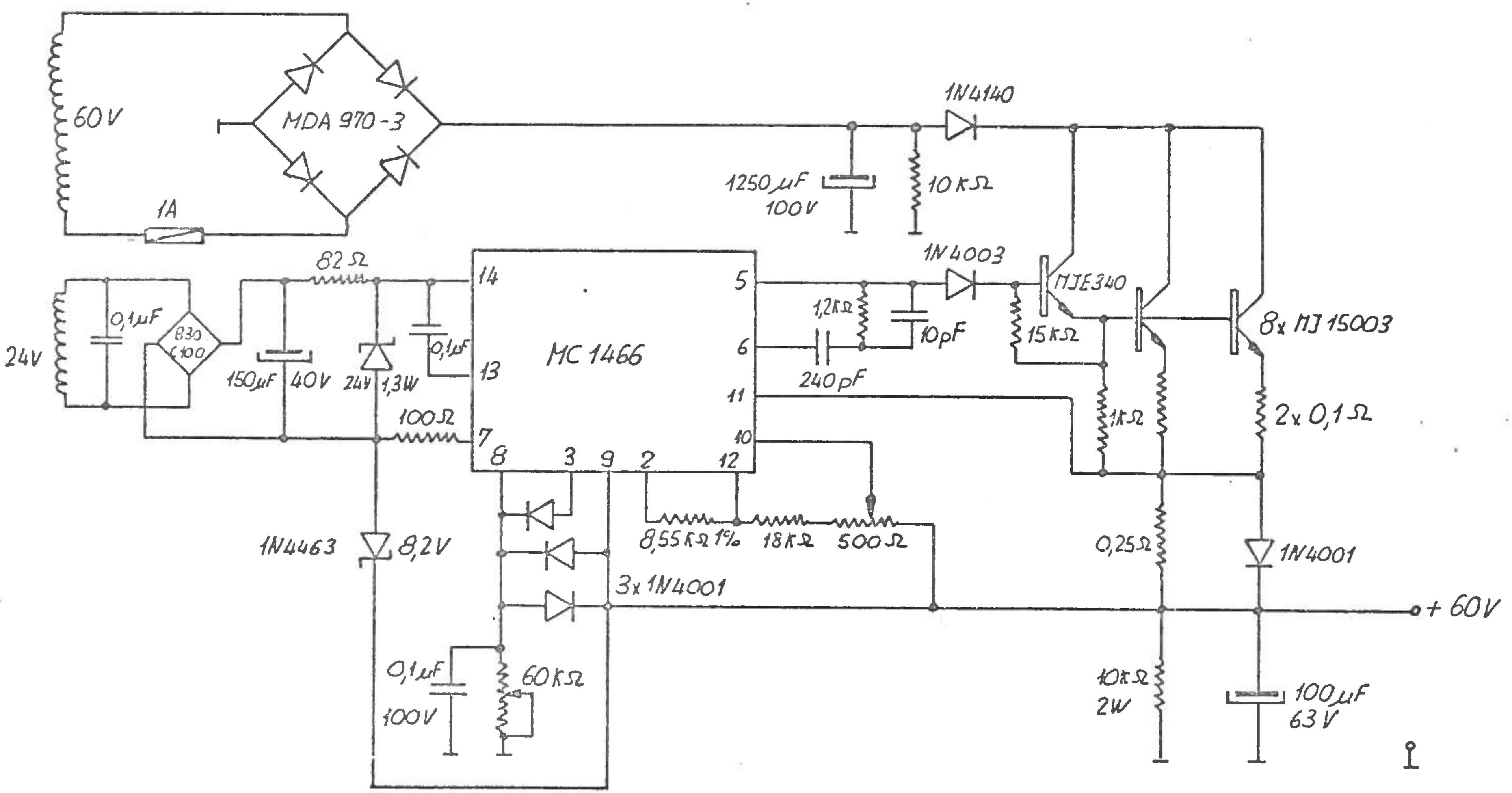


Fig. 3

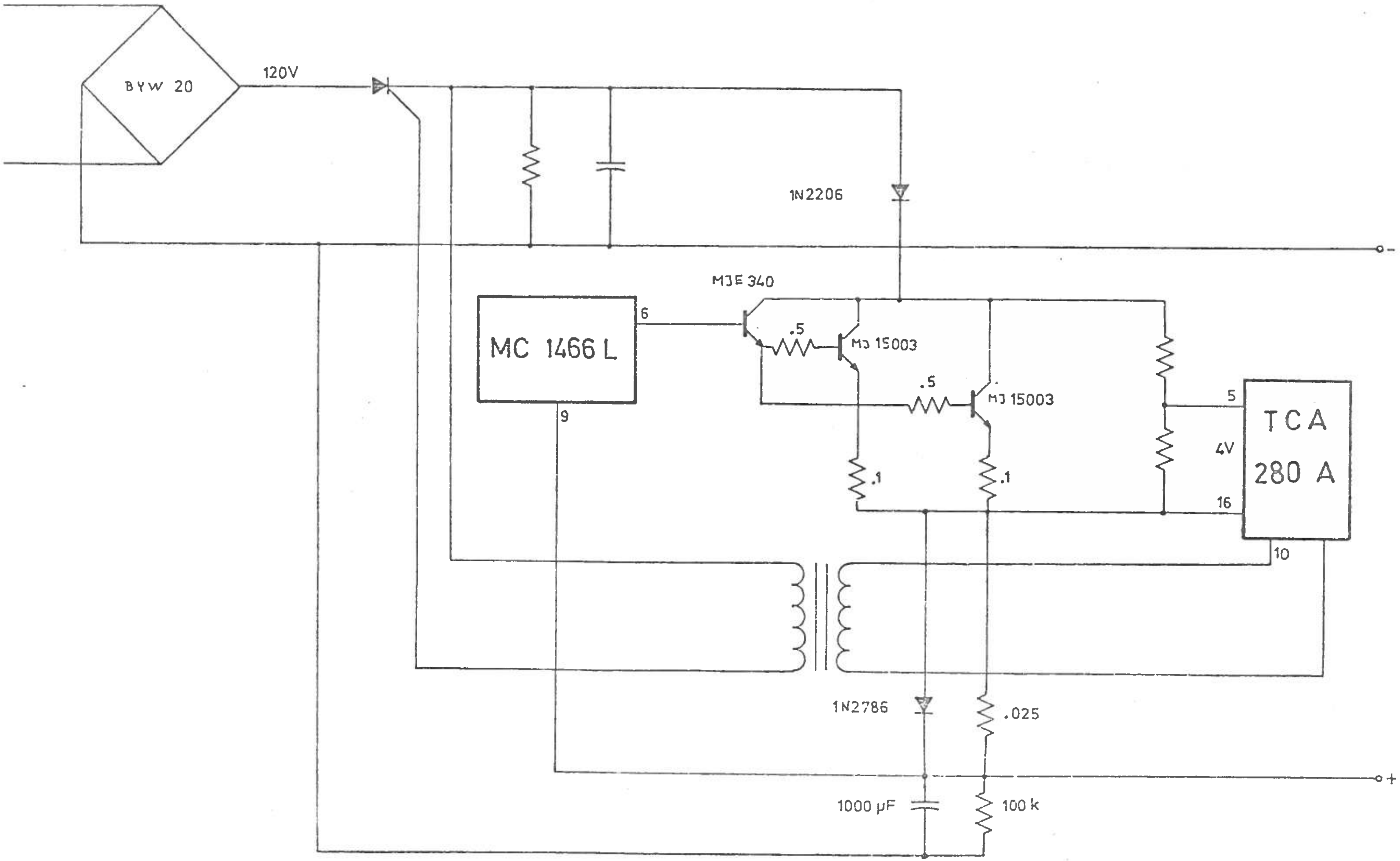

BYW 20
120V
1N2206
MJE 340
MC 1466 L
6
9
.5
MJ 15003
.5
MJ 15003
.1
.1
5
4V
16
10
TCA
280 A
1N2786
.025
1000 µF
100 k
-
+

Fig. 4

SWITCHING CIRCUITS

Thyristors DC Static Switches

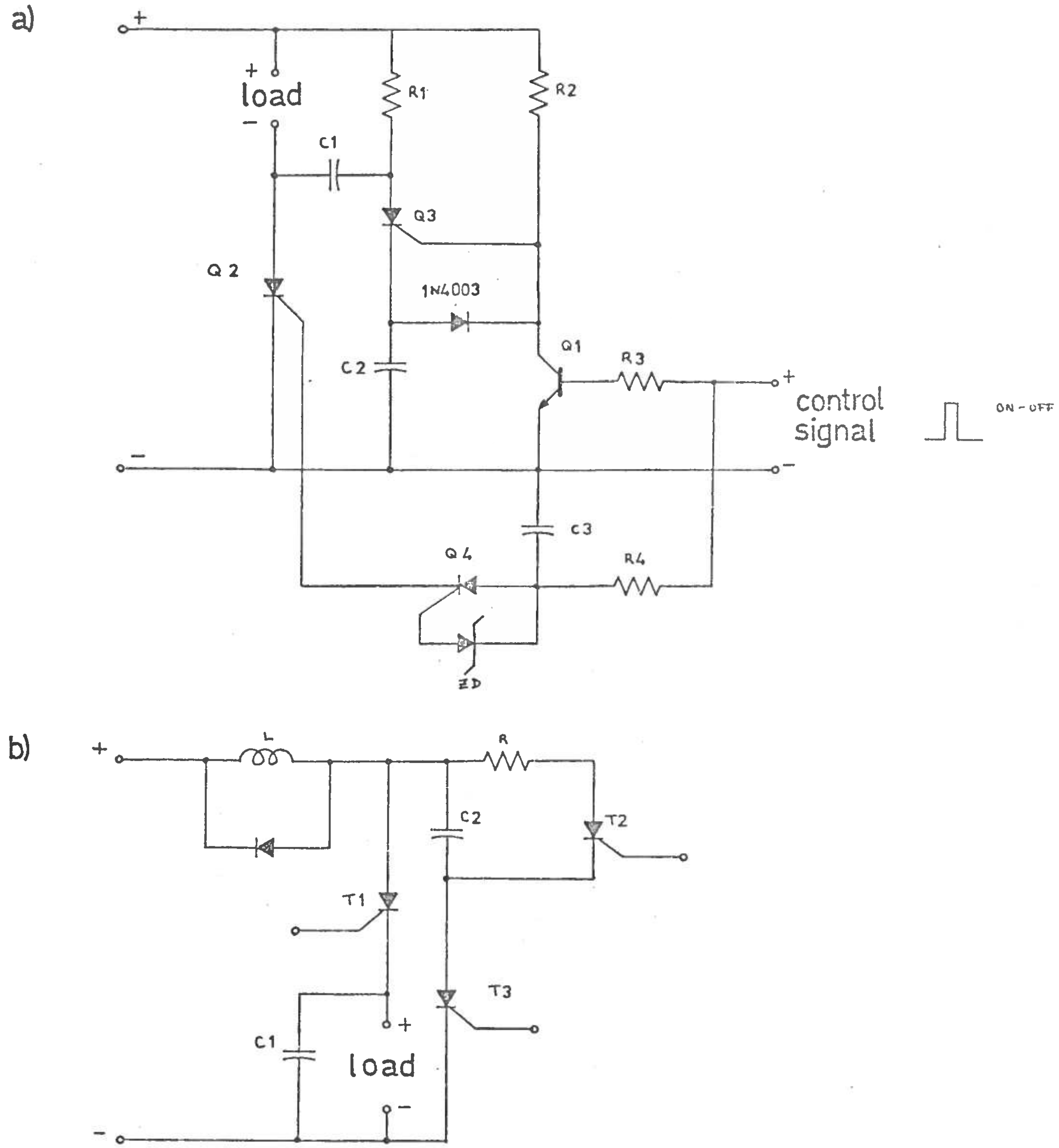
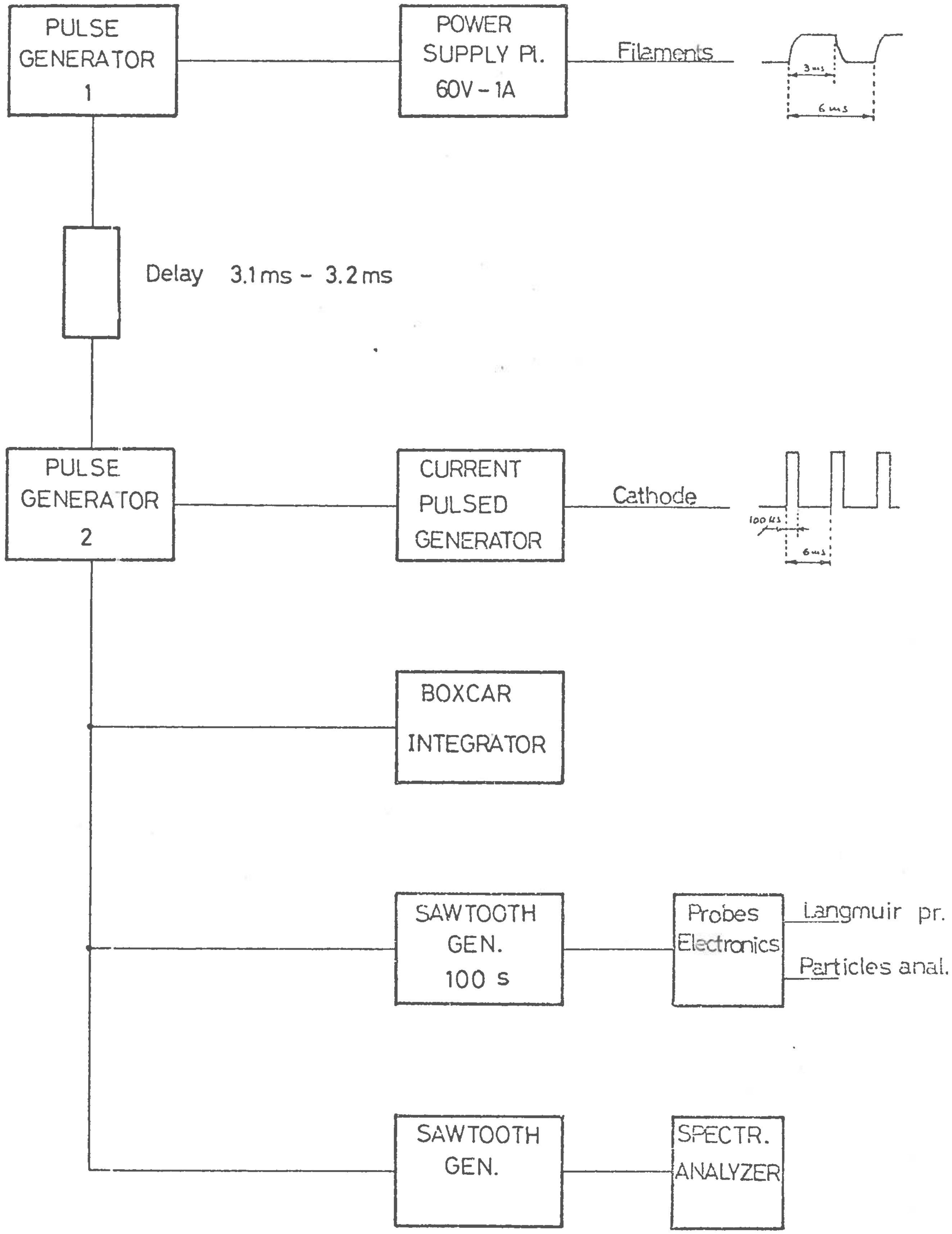


Fig.5



PULSE GENERATOR 1
POWER SUPPLY Pl. 60V - 1A
Filaments
3 ms
6 ms
Delay 3.1 ms - 3.2 ms
PULSE GENERATOR 2
CURRENT PULSED GENERATOR
Cathode
100 μs
6 ms
BOXCAR INTEGRATOR
SAWTOOTH GEN. 100 s
Probes Electronics
Langmuir pr.
Particles anal.
SAWTOOTH GEN.
SPECTR. ANALYZER

Fig. 6

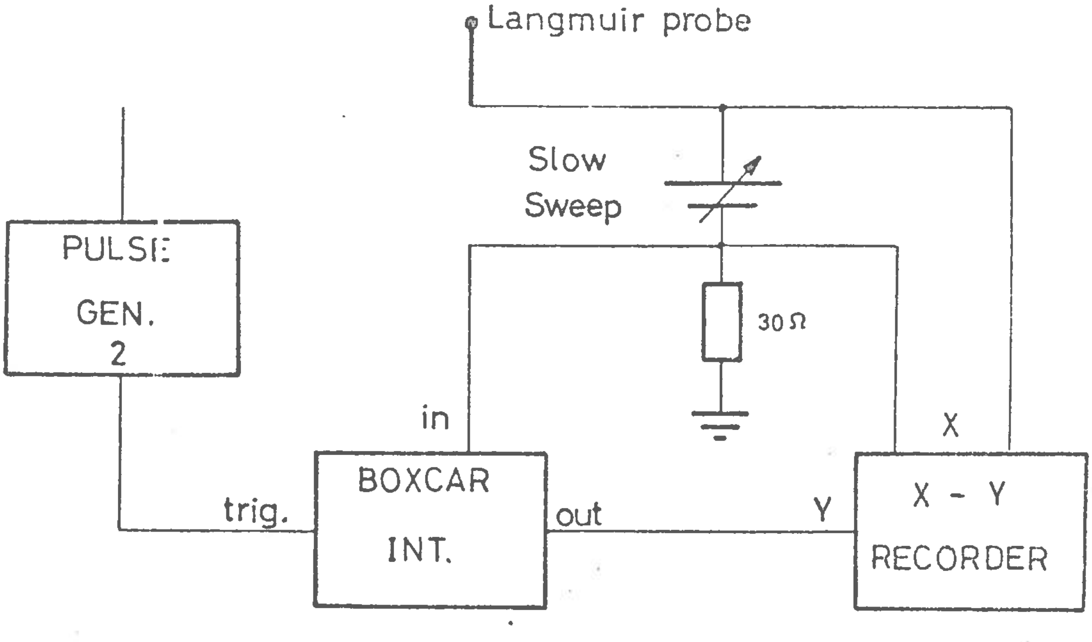

Langmuir probe
Slow
Sweep
PULSE
GEN.
2
30 Ω
in
X
BOXCAR
INT.
trig.
out
Y
X - Y
RECORDER

Fig. 7

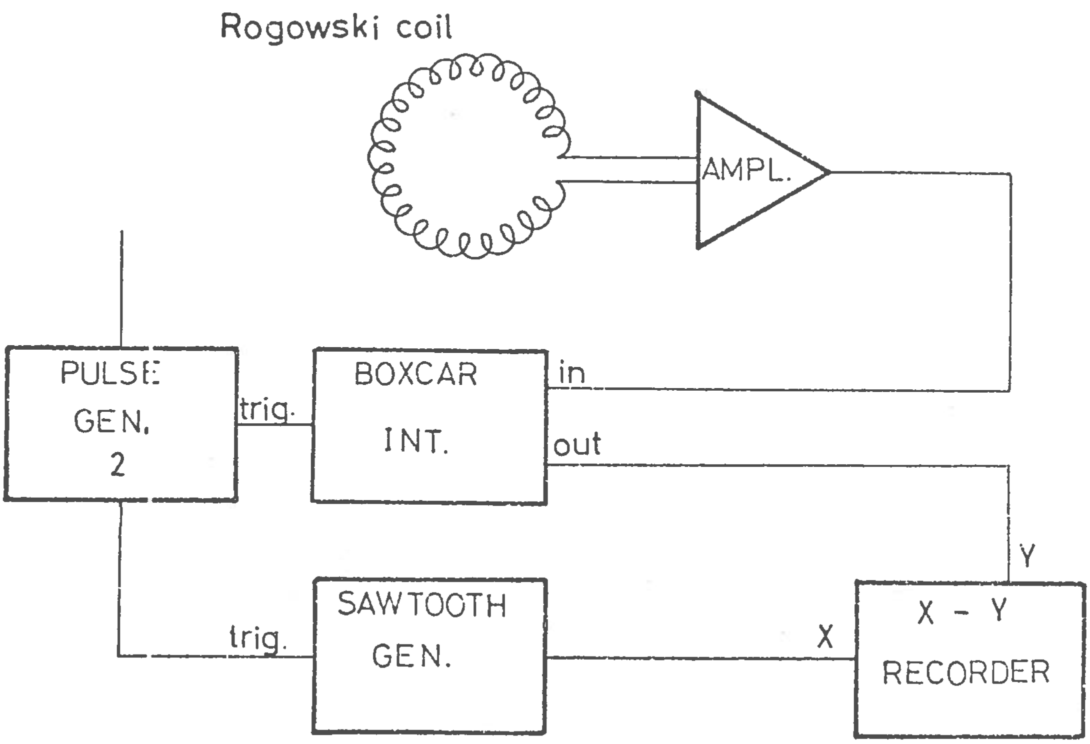

Rogowski coil
AMPL.
PULSE
GEN.
2
trig.
BOXCAR
INT.
in
out
Y
SAWTOOTH
GEN.
trig.
X
X - Y
RECORDER

Fig. 8

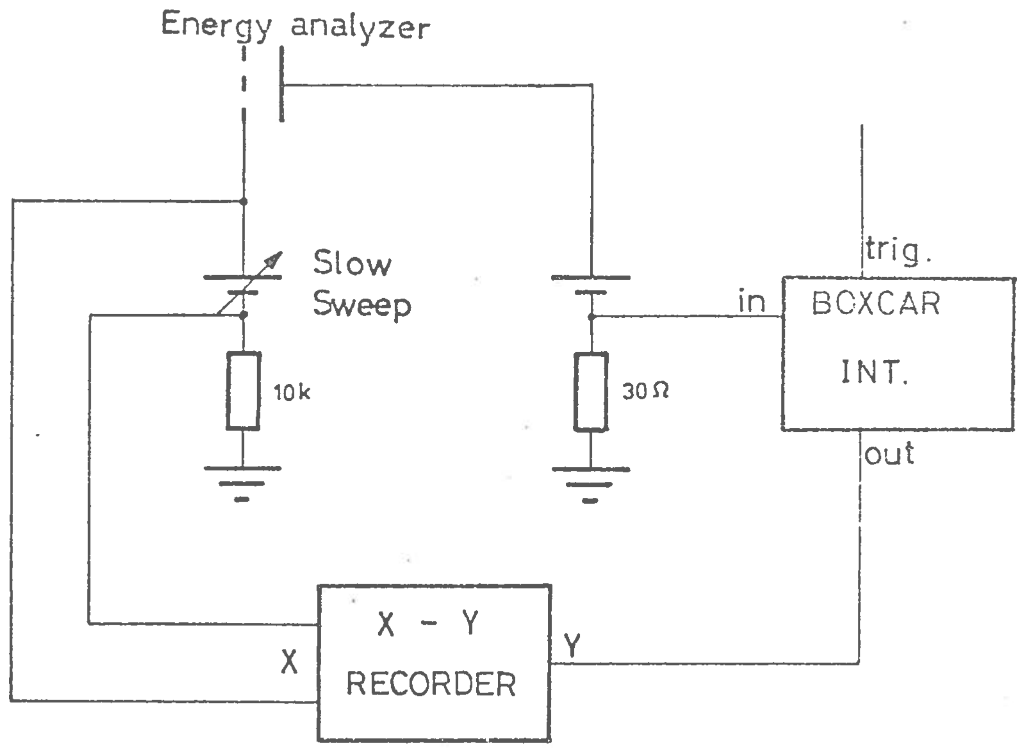

Energy analyzer
Slow
Sweep
10k
30 Ω
trig.
in
BOXCAR
INT.
out
X – Y
RECORDER
X
Y

Fig. 9

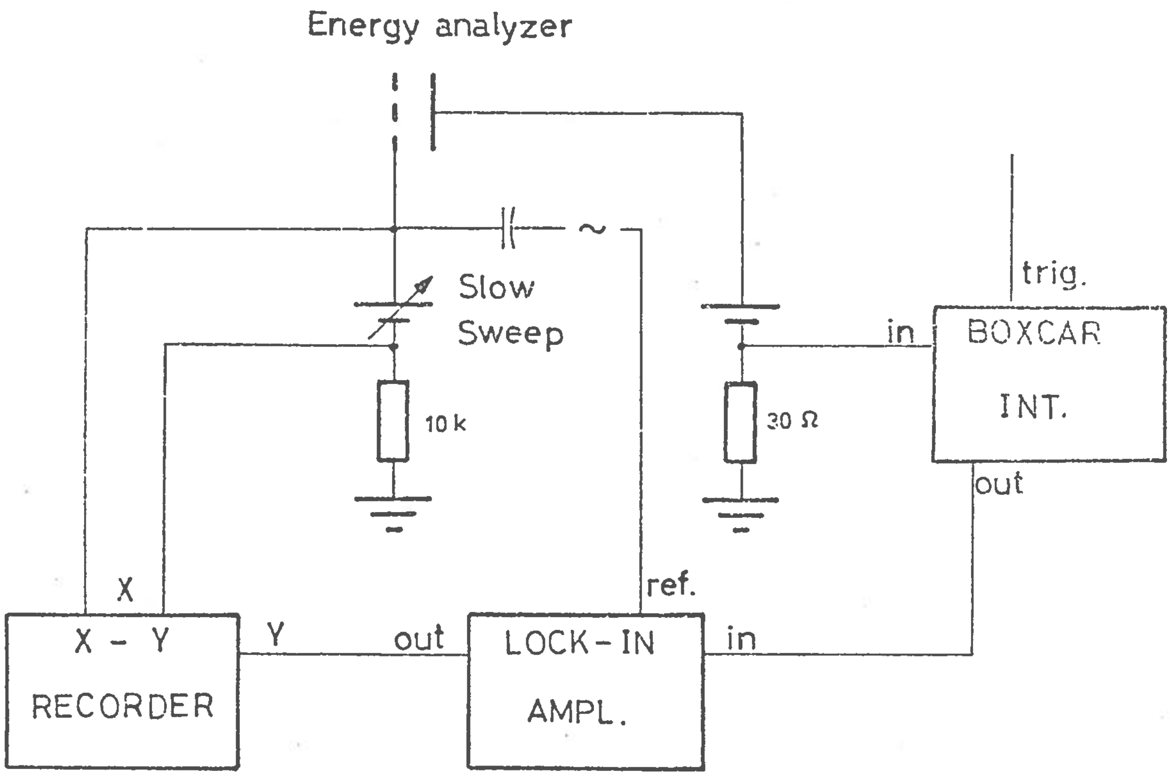

Energy analyzer
~
Slow
Sweep
10 k
30 Ω
trig.
in
BOXCAR
INT.
out
X
ref.
X – Y
RECORDER
Y
out
LOCK-IN
AMPL.
in

Fig. 10