CONSTRUCTION DETAILS AND TEST RESULTS
OF HIGH-VOLTAGE NANOSECOND
PULSE GENERATORS.

by

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1 INTRODUCTION.

The investigation of semiconductor materials and devices often requires the use of high electrical fields, generated by short voltage pulses to prevent considerable Joule heating or even thermal destruction of the samples. These pulses have to meet a number of requirements, e.g. they must have a nearly perfect rectangular shape with short rise and fall times, a flat top, a clean leading edge and a pulse duration from a few nanoseconds up to several microseconds.

In this report a description is given of the construction of a few high-voltage fast-rising pulse generators which are quite useful for the earlier indicated purpose.

After a brief explanation of line-type pulse generator theory, four separate discussions of such pulsers are given, all based on the same fundamental idea, but with different kinds of switches: mercury wetted contact relays, thyratrons, thyristors and avalanche transistors. Each description is completed with construction details, drawings and test results of the pulser concerned.

The report concludes with a comparison of the performance data and gives a number of suggestions for possible improvements and extensions.

2 A SUMMARY OF LINE-TYPE PULSE GENERATOR THEORY.

The design of a line-type pulser is relatively simple, because only a few components form part of it.

An open-ended transmission line (coaxial cable or lumped constant line) is charged to a potential $V_B$ by a high resistance $R_c$ (see Fig.1) and in the electrostatic field of the line is stored a quantity of electrical energy equal to $\frac{1}{2}C_t V_B^2$. $C_t$ is the total distributed capacitance of the line given by $C_t = C_1 l$ where $C_1$ represents the linear capacitance and $l$ the length of the transmission line.

Each time when the switch is closed, two travelling rectangular charge pulses are produced by the stored charge on the line, one of them travels to the right and one to the left. The right pulse is absorbed in the load, the left one is reflected at $R_c$ ($R_c$ is infinite in the ideal case) and joins the other pulse. So the pulse duration is twice the length of the line in time units and the pulse height is half the supply voltage if the line is well matched.

To discuss the operation of the pulser in detail, the basic circuit may be divided into two parts: the charging and the discharging circuit. Both arrangements will be described in the following parts of this section.
2.1 THE CHARGING CIRCUIT.

The charging circuit of a line pulser may be represented schematically as shown in Fig. 2.

If the switch is closed at the moment \( t=0 \), a positive voltage step travels down the open-ended fully-discharged transmission line from A to B, having an amplitude of \( \frac{Z_o}{Z_o + R_c} V_B \). At B this step will be completely reflected without changing sign owing to the open end and travels back to its starting point A. Because \( R_c \gg Z_o \), but finite, the step is again reflected without changing sign, but with a decreased amplitude. This process repeats with continuously decreasing steps until the voltage on the line is equal to the supply voltage.

The time needed for the charging of a particular line will be determined by the length of the transmission line and the magnitude of the charging resistance \( R_c \). Although there are three possible cases for this magnitude: \( R_c < Z_o \), \( R_c = Z_o \) and \( R_c > Z_o \), only the last situation is of importance, because \( R_c \) isolates the load from the voltage source during the discharge of the line.

The magnitude of \( R_c \) is determined by the following design data:

a) the maximum allowed difference in height between the first and the second half of the pulse,
b) the maximum allowed supply current,
c) the maximum d.c. current allowed to flow through the load when the switch is closed,
d) the duty factor of the pulse.

The first three points give a minimum value for \( R_c \), the last gives a maximum value.

If \( V_L \) is the line voltage, \( Z_o \) the characteristic impedance of the line,
the supply voltage, then the line voltage between the n-th and the
(n+1)-th step is given by

\[ V_1 = V_B \left(1 - \frac{R_c}{R_c + Z_0} \right) \]

in which \( t_d = \frac{R_c - Z_0}{R_c + Z_0} \) the charging reflection
factor is,

- \( t_d = \) twice the delay time of the line
- \( n = \) multiple of \( t_d \)
- \( t = \) time in which the switch is closed.

Fig. 3 shows the line voltage at A and B and the current through the line
as a function of time. The charging duration is several times the two-
way delay time of the line, so relatively slow. A good approximation of
the charging time is obtained by supposing the distributed inductances
are short-circuited and to calculate with the RC-time of the charging
resistance \( R_c \) and the total distributed shunt capacitance \( C_t \) of the
line. The charging is approximately finished after 3 to 5 times \( R_c C_t \).
The minimum interval time during two discharges and thus the maximum
repetition frequency will be determined by the time needed to re-
charge the line after the discharging circuit has been disconnected from the line.

Because of the dissipative nature of \( R_c \), the efficiency of the charging
is not very high. Substitution of \( R_c \) by an inductance is possible but
will not be discussed here, for the efficiency is not important in the
pulsers we need.

2.2 THE DISCHARGING CIRCUIT.

Fig. 4 indicates schematically the discharging circuit of a line pulser.
If the line is lossless, the switch in the closed situation has no
resistance, the load is pure resistive and equal to \( Z_0 \) of the line which
is charged to a potential \( V_B \), the following things will happen when the
switch is closed at \( t=0 \). A negative voltage step with magnitude \( \frac{1}{2} V_B \)
travels down the open-ended line from A to B, while a positive step, also
with magnitude \( \frac{1}{2} V_B \) appears across the load. The step reflects at B
without changing amplitude and sign and travels back to A, delivering
the total stored energy of the line into the load, leaving the line
completely discharged after twice the delay time (Fig. 5b). However this is only one of the three possible values which the load resistance can possess: $R_o > Z_o$, $R_o = Z_o$ and $R_o < Z_o$.

In the case $R_o > Z_o$ a reflected pulse is produced at the load with the same polarity as the incoming pulse. Across $R_o$ now appears the sum of the two pulses and thus a voltage which is greater than $\frac{1}{2} V_B$. The reflected pulse travels through the connecting line and the discharging line, reflects again at the end of the latter and travels back to the load $R_o$. This process repeats until all the energy present in the discharging line at $t=0$ is dissipated in the load. The voltage across $R_o$ will have a similar shape as is shown in Fig. 5a.

In the case $R_o < Z_o$, the voltage step coming back to $A$, is also partially reflected at $R_o$ but has a negative polarity, so at the load a voltage is produced that is the difference of the arriving and the reflected pulse. This negative step travels up the connecting line and the discharging line, reflects at $B$ without changing sign and the step changes its sign as it reaches the load, and so on. This leads to a decreasing alternating waveform as is shown in Fig. 5c. Only in the matched case when $R_o = Z_o$, a perfect rectangular voltage pulse appears across the load, but in all three cases, the stored energy in the line is dissipated in the load, only the time in which this happens is different.

If $V_B =$ the supply voltage $V_o =$ the output voltage $Z_o =$ the characteristic imp. of the line and $R_o$ the load resistance, then the pulse voltage across the load, during the $(n+1)$-th step is given by

$$V_o = \frac{R_o}{R_o + Z_o} \cdot V_B \cdot R_d^n$$

in which

$$R_d = \frac{R_o - Z_o}{R_o + Z_o}$$
\( t_d \) is the two-way delay time of the line and \( n \) is a multiple of \( t_d \).
In the case \( R_o = Z_o \) the pulse duration \( t_p \) is equal to twice the delay time of the discharging line.

2.3 COMBINED CIRCUITS.

The charging and discharging circuit can be joined together, as shown in Fig. 6. There is no essential difference in performance of the pulser when connecting \( R_c \) with A instead of B, but the switch may be enclosed in a coaxial line to decrease possible reflections due to mismatch, so it is often easier to connect \( R_c \) with the free end of the line.

In the configuration of the pulse generator as indicated in Fig. 6, the charging resistor is always connected to the line in a way that a certain d.c. current flows into the load as long as the switch is closed.

To prevent inadmissible heating of the load, this current has to be limited by giving \( R_c \) a value as high as possible. This influences however the maximum attainable repetition frequency of the pulser, so a compromise has to be made.

Fig. 6

As appears from section 2.2, the shape of the output pulse will be determined by the elements which form part of the discharging circuit: transmission line, switch, load and the connections between these components. Although in our investigation the semiconductor samples mostly represent a more or less resistive behaviour, their magnitude will probably be not equal to \( Z_o \) of the line. If a rectangular pulse shape has to be maintained, a resistor must be connected either in parallel or in series with the sample, to match the line.

The pulse forming line may be a certain length of coaxial cable for short pulses or a lumped-constant transmission line, if pulse durations of several microseconds are needed.

Using a correctly designed lumped line, it is possible to generate a fast-rising flat pulse with little ripple and sufficient duration. When using coaxial cables, the choice of \( Z_o \) is limited to some commercially available impedances. Cables with an impedance of 50 ohm are often used in laboratory work.

More freedom gives the application of lumped lines, although here the available constant impedance connectors can limit the design.
In section 2.2 it has been assumed that the contact resistance of the switch is zero, which is in general not true. Only when a mercury wetted contact relay is used as the switch, the voltage drop may be neglected, for such a relay has a resistance of about 10 to 50 milliohms.

A time-independent switch resistance has the same influence on the pulse shape as a load \( R_o > Z_o \) which is connected to the line (see Fig. 5a). However, if the switch resistance is time-dependent, the voltage drop across the switch changes during the pulse and so the pulse shape changes. Besides a contact resistance diminishes the available pulse amplitude.

Taking e.g. a thyratron as a switch, then the leading edge of the output pulse will be determined by the ionization time of the tube, which process is slightly influenced by the magnitude of the supply voltage: a higher \( V_B \) gives a higher \( V_o \) with shorter risetime.

The line-type pulser has the benefit of great simplicity, but also shows some disadvantages:

- a change in pulse duration is only possible by connecting another transmission line (with longer or shorter delay) to the pulser.
- it is mostly not possible to trigger an external instrument, e.g. an oscilloscope with the driving oscillator of the switch, due to the time jitter between the driving and the output waveform.

So the trigger signal has to be taken from the output pulse itself which sometimes has to be delayed.

Another problem is the possibility of changing the output pulse polarity. No difficulties arise when using a mercury wetted switch: only changing the polarity of the supply voltage is sufficient to get a negative pulse with the same shape. If an electronic switch is used, this action is not so easy, because the current through the switch can flow only in one direction (in general). The fastest way here is using a high-quality pulse transformer to change the polarity.

If only negative pulses are needed, the load may be inserted in the connection from earth to the outer conductor of the line, as shown in Fig. 7. Care has to be taken to isolate the whole line, because the outer conductor rises to a high potential during the pulse.

A number of suitable switches will be discussed in the next following sections.

Fig. 7. Circuit connection for negative pulses.
The usefulness of mercury switches in line-type pulse generators depends on two important properties which they have, namely the complete absence of contact bounce through which multiple pulses could be generated having different amplitudes due to partial charging of the line and the small time needed to make or break the electrical contact.

The switch consists of a sealed glass capsule, a moving armature with a capillary path from the mercury pool to the contacts to keep them continuously wetted and a few stationary contacts. When a magnetic field of appropriate strength is applied, the armature moves and a filament of mercury is drawn between it and the normally closed contacts, joining all contacts for a moment as is shown in Fig. 8.

At a certain moment, this filament breaks extremely fast (within 1 ns).
A similar action occurs on release.

The capsule is hermetically sealed and contains a hydrogen filling under high pressure, which performs many functions.
It keeps the mercury clean, provides a non-oxidizing atmosphere, quenches the arc, conducts the generated heat at the contact points and retards mercury vaporization and ionization.
A pulse generator which contains such a relay, can deliver single fast-rising pulses with amplitudes up to a few thousand volts, depending on the type used. The switch opens when the pulse current has already decreased to zero, so the contact is broken dead and no voltage peaks will be induced in the circuit.

3.1 CONSTRUCTION OF A PULSER WITH A CLARE RP5441 CAPSULE.

A special coaxial housing has been designed to diminish reflections by lead inductance and to approach a 50 ohm line as close as possible. In Fig. 9 the several parts of the housing are drawn. Fig. 9a shows the outer conductor. The smallest inner diameter on the place where the capsule has been mounted, is chosen to be about 0.2 mm greater than the diameter of the switch itself, to safeguard it against possible vibrations which could break the glass cover. While some spreading in mercury pool dimensions is common, the dimensions of the round excavation represent
an average of the needed outer diameter on that place. The dimensions of the housing have been matched to the widely used General Radio 874 connectors, placed on each side. The capsule is shown in Fig. 9b and the short inner conductors have been drawn in Fig. 9c, showing the slots which have been made to fasten the contact leads of the switch by turning the small screws. The assembly of the coaxial switch is given in Fig. 9d. Brass has been used for the metallic parts. A coilform has been installed round the outer conductor with 10,000 turns of enameled copper wire, 0.15 mm in diameter, having a dc-resistance of 1000 ohm. The minimum ampere-turns to drive the switch is 150 A.T.

Fig. 9 Drawing of the housing for a Clare RP5441 M.W.C.R.
After the composition of the coaxial switch a T.D.R.-measurement has been carried out, to determine the remaining reflections.

A Hewlett Packard 1415A Time Domain Reflectometer was used for this purpose. The observed curves are shown in Fig. 10a and 10b, indicating the T.D.R. display as seen respectively from the stationary contacts and from the mercury pool side. The switch was in the upright position during this measurement and the contacts were closed by a d.c. current through the coil. The free connector was terminated with a 50 ohm load. The curves show that the maximum appearing reflection coefficient in the housing is 0.075 (in both cases), so equivalent with an impedance of 58 ohm based on the 50 ohm level.

These reflections are due to the irregular shape of the inner conductor inside the mercury capsule. The small dimensions of the armature make it impossible to maintain the necessary outer to inner conductor diameter ratio of roughly 2.3 for a 50 ohm air line, not even when the outer conductor touches the glass capsule.

If the coaxial housing would be designed for a 75 ohm impedance system perhaps an entire absence of reflections could be achieved.

![Fig. 10a Reflection coefficient as seen from the fixed contacts.](image1)

![Fig. 10b Reflection coefficient as seen from the mercury pool side.](image2)

The assembly of the whole pulser has been sketched in Fig. 11. The coaxial switch is mounted with two supports against a vertical front plate with the mercury pool down. To both sides of the housing a coaxial knee-piece is installed (General Radio 874 with locking connectors). The lower knee is connected with a G.R.-8/4 front panel connector and this plug is the output of the pulser.

The transmission line is connected to the opposite side of the housing and to a plug on the back plate of the pulse generator house. Between this plug and a high tension plug a power charging resistor has been
soldered. The coil leads are connected with a BNC plug on the front panel. To drive the mercury relay a special oscillator has been built which delivers a rectangular waveform of 4.5 ms duration and an amplitude up to 50 V. The frequency is variable from 10 Hz to 10 KHz in three decade steps with fine control. However, the mercury switch works well up to 120 p.p.s. The special shape of the driver signal decreases the closed period of the switch.

Fig. 11 Sketch showing the construction of the pulser.

3.2 PERFORMANCE.

The output pulse across a 50 ohm termination was observed on a Tektronix sampling oscilloscope with 50 ps rise time and the curves were recorded by a XY-recorder, so a copy of the screen display was obtained. In this measurement the voltage on the transmission line was 1 V, to avoid the use of attenuators. The trigger pulse was taken from the output pulse by means of a resistive microwave signal sampler and the main pulse was delayed by a length of corrugated air-spaced semiflexible cable to limit the influence on the rise time of the pulse.

Fig. 12 shows the leading edge of a 320 ns output pulse with an amplitude of 0.5 V and an observed rise time (10 to 90 p.c.) of 375 ps.

Fig. 12
Typical output pulse shape of a M.W.C.R. pulser.

Horizontal scale: 0.5 ns/cm.
The repetition frequency was 60 Hz.

As appears from this curve the leading edge of the pulse is clean. After the fast-rising part of the pulse the curve rises slowly in about 10 ns to the full amplitude and stays there for the remainder of the pulse duration. The ripple on the top during the first 3 ns is caused by the reflections inside the coaxial housing and the oscillation does not vary with supply voltage, pulse duration or matching conditions. Some attempts have been carried out to decrease this ripple but without appreciable result. Probably no better performance can be achieved with this particular type of mercury wetted relay. To obtain still a good pulse shape for measuring purposes, the pulse could be filtered by a low pass filter.

This has been done, using a lumped-component device with a rise time of about 2 ns. The waveform which is then available is shown in Fig.13. A coaxial filter with 600 ps rise time and capable for 3 kV has been designed by van Welzenis and Sens (see ref. 17).

![Filtered pulse](image)

Small changes in the leading part of the pulse are possible when exchanging capsules of the same kind.

The maximum pulse amplitude achieved with this relay before breakdown occurs differs from relay to relay but lies in the order of magnitude of 2.5 kV into 50 ohm.

The pulse shape does not change when the supply voltage or the repetition rate is increased. Both polarities can be generated with this pulser.

3.3 A PULSER WITH A HAMLIN HRC-1 CAPSULE.

Also for this type of mercury relay a special coaxial housing has been made. The stationary and the moving contacts of this switch have a more
regular shape for they consist only of thin metallic straps, one of them is continuously wetted by adhesion of mercury. The fine mercury drops move by the vibrating action of the armature.

The different parts and the assembly of the housing are indicated in Fig. 14. G.R.-874 connectors have been used in the design.

Care is taken to prevent collision of the glass capsule with the outer conductor (Fig. 14a) by making the inner diameter of this conductor about 0.2 mm larger than the diameter of the glass cover. The connection of the switch leads is made by the clamping fingers of the inner conductors.

Fig. 14 Drawing of the housing for a Hamlin HRC-1 M.W.C.R.
All metallic parts are of brass. On a P.V.C.-coilform 7000 turns of enamelled copper wire, 0.15 mm in diameter have been wound and 100 AT. are sufficient to drive the switch.

After assembly of the parts a reflection measurement was carried out just as was done with the Clare relay, also with the switch in vertical position and the contacts closed. The results are indicated in Fig. 15a and 15b for respectively the stationary contacts side and seen from the mercury pool side. As could be expected from the regular shape of the contact blades, the reflection coefficient has been diminished compared with the Clare switch, although they are still considerable. This is probably due to the armatures, which are regular and about 2.5 mm wide, only have a small thickness. The remaining reflection coefficient of 0.065, corresponding to an impedance of 56.5 ohm and based on the 50 ohm level, can be improved a little perhaps, but also in the case that the outer conductor touches the glass capsule, there is still a large reflection left.

Fig. 15a Mercury pool side. Fig. 15b Stationary contacts side.

This coaxial switch is mounted in a similar way as is sketched in Fig. 11 and the performance tests which have been carried out are based on the same conditions as described in section 3.2.

Fig. 16 shows the leading edge of the output pulse on a horizontal scale of 200 picoseconds per cm.

A rise time of 250 ps is observed between the 10 and 90 p.c. points. After about 6 ns (see Fig. 17) the pulse reaches its final value and maintains a flat top. Pulse amplitudes up to 1000 V in both polarities can be achieved with this relay before breakdown occurs. A remark must
be made on the appearance of some contact bounce in certain regions of the repetition frequency, between 0 and 100 Hz. Changing the actuating voltage decreases or eliminates this symptom.

Fig. 16
Leading edge of the output pulse.
Hor. time scale 200 ps/cm

Fig. 17
Leading part on a time scale of 1 ns/cm.

The application of mercury wetted contact relays in line-type pulsers show some clear advantages and disadvantages. Pro M.W.C.R. are the achievement of fast-rising high-voltage pulses of both polarities, the simplicity of the pulser design, its low effective switch resistance, small dimensions and the possibility of driving the relay with a low voltage. Contra the mercury switch are the limitation of the repetition frequency and the large time jitter.

4 THYRATRON PULSERS.

A summary of the operation of a thyatron may be given well on the basis of the sketch in Fig. 18, where a cross-section is given of the tube. To enable high currents to pass through the tube, the gas-ionization phenomenon may be used to escape to the limited cathode emission of a vacuum tube. Across the tube a voltage drop exists and if it becomes too large the oxide cathode will be destroyed. Filling the bulb with hydrogen allows the use of high currents before the so-called destruction voltage of hydrogen is reached. Another reason why hydrogen is used is the short deionization time of this gas.
The grid is placed on a short distance of the anode to permit high gas pressure in the tube, necessary owing to gas cleanup. The anode is completely surrounded by a grid structure and the cathode is also shielded. So, the anode field does not act upon the electrons emitted by the cathode and they stay inside the cathode shielding. To start ionization of the tube a current has to be drawn between the grid and the cathode, generating carriers outside the shielding. They fill the region between cathode and grid baffle. Now the anode field can act upon electrons and ions surrounding the grid baffle and ionization occurs in the grid-anode region. Current starts to flow through the tube and the anode voltage drops quickly to a low value. The time in which this happens until an almost constant value of the voltage drop across the tube has been reached, is called the ionization time. It is characteristic for a particular type of thyatron and almost entirely independent of external conditions.

The voltage drop and the effective impedance of the tube are functions of time, they decrease very fast during the ionization period and remain nearly constant during the conduction period.

The application of a hydrogen thyatron in a line-type pulser to generate high voltage pulses is often used because of its excellent properties. It can be triggered precisely with small delay and time jitter using a medium-voltage trigger pulse. The delay and the time jitter depends on the trigger amplitude, its rise time and the anode voltage of the thyatron. A shorter rise time of the trigger signal decreases the delay. Also important is the fact that no bias voltage is needed as long as the repetition frequency is relatively low, which simplifies the trigger circuitry.

The repetition frequency is limited by the deionization time. To prevent constant conducting of the tube after the output pulse has been disappeared, the voltage across the tube must be kept low. So a high charging resistor must be used to enable the thyatron to deionize. The thyatron behaves like a switch with a low internal resistance, although this resistance is a function of time. This influences the pulse shape, so the rise time of the output pulse of a thyatron-equipped line pulser will be determined by the ionization time of the tube.
To achieve a rectangular pulse form, the sum of load impedance and internal impedance must be equal to the characteristic impedance of the transmission line. If the load and the line impedances are both 50 ohm, a similar waveform arises across the load as shown in Fig. 5a.

4.1 A PULSE GENERATOR USING A FX2513 THYRATRON.

This thyratron has been mounted in a circuit as shown in Fig. 19 schematically. The charging resistor is connected to one side of a grounded 50 ohm transmission line of a certain length and the anode of the tube to the other end. The trigger pulse is applied by means of a 1:4 step-up pulse transformer to the grid, to achieve a sufficient high trigger amplitude. Both windings of the transformer must be carefully isolated from each other and the capacitance from primary to secondary winding has been decreased by winding them on opposite places on a round torus. The diode eliminates possible backswing to safeguard the trigger generator. A d.c. current of 2.7 A is applied to the heater and no bias is used. The value of the charging resistance must be adapted if long pulses and high repetition rates are needed.

The heater supply is isolated from the pulse by a low-pass filter which consists of four bifilary wound chokes of 0.8 mH each and a 22 mF capacitor. The chokes have been wound on potcores in such a way that the d.c. magnetization is decreased, for the d.c. currents in the windings now travel in opposite direction to each other round the core. Some information on these components is given later.

A sketch of the mechanical construction of the pulser is shown in Fig. 20. The tube is mounted in a brass cylinder, provided with some holes in the upper and lower part of the housing to accomplish air-cooling. A more or less coaxial line has been approached in this way, although the expected pulse rise time will not be so short that lead inductance starts to play an important role.

The cathode is connected directly by a short piece of coaxial line to the output connector on the front panel. The heater leads inside the housing up to the tube base have been decoupled by ferroxcube rods. The tube housing is mounted horizontally between the front and the back panel of the generator house. Fig. 20b gives the arrangement of
the remaining components and in Fig. 20c is shown the charging-resistor box. So the most suitable value of the resistance in a particular measurement can be chosen. The storage line is connected with one side to the pulse generator house and with the other end to the charging-resistor box.

Fig. 20 Assembly of the thyratron pulser.

4.2 OPERATION DATA.

Owing to the minimum required anode voltage of about 300 V the output pulse has to be attenuated before it can be connected to the measuring instruments.

With commercially available attenuators and signal samplers only a few hundred volts can be handled. To make it possible to test the pulser at full output, special resistive bleeders have been constructed with "home made" resistors. These are deposited metal film resistors on a flat glass substrate capable to handle up to 2.5 KV pulse voltage with durations to 1 us and a rise time better than 2 ns.

Such a resistor is inserted in a stripline signal sampler as shown in
Fig. 21a. The pulse arrives at the left connector, passes through the stripline and leaves the tap-off almost without attenuation, for the resistance in the side arm is sufficient high (5 Kohm). The signal from the side arm can be attenuated further with coaxial devices to a level suitable for the input of the oscilloscope.

A similar tap-off is used to achieve the necessary trigger pulse, as is indicated in the block scheme. With this circuit the performance data of the thyatron pulser have been measured. The repetition frequency was 80 Hz.

Fig. 22a-c on page 20 shows the leading edge of the output pulse with an amplitude of 500V, 1 KV and 2 KV. The entire pulse form of 750 ns width is indicated in part d of that figure. No bias is applied to the tube during these measurements.

As may be seen from the curves, the rise time of the pulse is slightly dependent of the pulse height, which could be expected from the decreasing ionization time of the tube when the anode voltage is increased. The results are given in the following table

<table>
<thead>
<tr>
<th>( V_o ) (V)</th>
<th>( t_r ) (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>23</td>
</tr>
<tr>
<td>1000</td>
<td>19</td>
</tr>
<tr>
<td>2000</td>
<td>18</td>
</tr>
</tbody>
</table>

The pulse generator has been tested at repetition rates up to 5 KHz with a 50 ns pulse and a suitable value of the charging resistor. However, higher frequencies are possible. The maximum recovery time of the tube is about 17 \( \mu \)s, when no bias is applied and when the maximum allowed current of 40 A flows.

The trigger pulse which is used has an amplitude of 110 V (into 50 ohm) at the input of the pulse transformer, a rise time of about 25 ns and a duration of 5 \( \mu \)s. Shorter trigger pulses will also do the job, but each time when a thyatron output pulse of a few microseconds is used, the trigger pulse width must be adapted, so one single trigger duration is chosen. It is long enough to drive the tube also when microsecond pulses are needed. The trigger signal was delivered by an
Fig. 22. Output of thyatron pulser.
avalanche trigger amplifier which will be discussed later.

The tube can supply a peak pulse power of 140 kW. It has a maximum anode voltage of 8 kV and can deliver a peak cathode current of 40 A.

The output of the pulse generator can be varied between 150 and 2000 V. No attempts have been made to change the circuit for delivering negative output pulses.

4.3 SOME EXPERIMENTS WITH A TUNG-SOL 7190 THYRATRON.

The 7190 is a zero bias miniature hydrogen thyratron which can supply peak pulse power of 10 kW, hold 1200 V anode voltage, can handle 20 A peak current and is suitable for pulse repetition frequencies up to 5 kHz at full current rate. Higher repetition rates are possible but an average anode current of 50 mA must not be exceeded. The current rate of rise is 0.4 A/ns.

4.3.1 Pulser with positive pulse polarity.

The scheme of Fig. 19 has been applied for building the generator and also the same kind of low-pass filter. An analogous pulse transformer (however with turns ratio of 1 to 2) was used. The resistance in series with the grid has been lowered to 220 ohm. A heater current (d.c.) of 1.8 A is necessary for proper operation and a trigger pulse of 110 V is fed into the primary of the transformer.

In Fig. 23 a sketch is given of the formation of the generator components. The tube has a small button 7-pin miniature base and its connections will be given later in this report.

![Diagram of generator assembly](image)

**Fig. 23** Generator assembly.

The measurements of the generator properties have been carried out in a similar way as was described in point 4.2 of this section. Also a repetition rate of 80 Hz was chosen to record the curves shown in Fig. 24.
Part a of this figure indicates the shape of a 300 ns pulse with an amplitude of 550 V, while part b shows the leading edge of this pulse for several pulse heights.

It must be concluded from the curves that the pulse shape is good. The leading edge is clean and the top of the pulse is flat after about 100 ns. There are almost no ripples.

The rise time decreases which increasing pulse amplitude from 21 ns to 15 ns when the pulse is increased from 200 V to 600 V. (the pulse height at 70 ns is taken as the 100 p.c. level).

It is possible to influence the rounded corner of the leading edge (due to the ionization effect) by connecting a capacitance of suitable value across the storage line at the anode side, because the discharge of a capacitance will achieve a higher amplitude into 50 ohm than a line with characteristic impedance of 50 ohm does, so the corner could be sharpened.

---

**Fig. 24a**
Total view of a 300 ns pulse.

Hor. time scale 50 ns/cm

---

**Fig. 24b**
Leading edge for different pulse heights.

Hor. time scale 10 ns/cm
4.3.2. Pulser with negative polarity.

For this experiment the scheme of Fig. 25 is used. The outer conductor of the pulse shaping line is charged towards the supply voltage and the inner conductor is connected to the load. It is not essential for the operation of the pulser whether the outer conductor is charged or the inner one. In Fig. 25b is sketched the experimental frame of the generator (bottom view). Only one end of the storage line is used, the other one has been isolated.

An important construction part is the double connector. The outer conductors of two N-type connectors have been isolated from each other by using small teflon tubes and screws. The inner conductors have been soldered together. The output terminal is earthed while the other conductor (free from earth) has been connected to the line, to the anode of the tube and to the charging resistor. This kind of set-up makes the use of a filter in the heater leads and a pulse transformer in the grid circuit unnecessary.

The trigger pulse is now capacitively coupled to the grid and the 50 ohm resistor terminates the trigger generator. A trigger pulse with a height of 200 V has been applied to the grid with the same width as the main pulse. The test results of this generator are indicated in Fig. 26a and 26b, showing the leading edge at different pulse heights and the total pulse of 300 ns respectively.

![Figure 26a](image-url)
4.3.3. Series operation of two 7190 thyatrons.

To increase the amplitude of the output pulse, two (or even more) thyatrons may be connected in series. The number is limited by the peak current which is allowed to flow through the tubes. The arrangements for this experiment are shown schematically in fig. 27.

The pulser is capable of delivering a positive pulse of maximum 1100 V into 50 ohm with short rise time (20 ns) using a supply voltage of 2.4 kilovolt. A negative amplitude will be achieved when the load is inserted in the connection between the outer conductor of the line and earth.

Two separate heater supplies are needed owing to the voltage difference between the two tubes. Both heater supplies have to be well isolated from the pulse by means of low-pass filters as indicated earlier.

To achieve an equally division of the available high-tension, a 1 Mohm resistor has been mounted across each tube.

Discharging of the line is obtained by triggering the lower tube, which starts to ionize, so the voltage across this tube collapses and the cathode potential of the upper tube is lowered. Due to the internal capacitance of the anode-grid region, the grid tries to maintain its potential level of about half the line voltage for a very short moment. So it looks like pushing a positive voltage step on the grid of the upper tube which also starts to conduct.

The time difference between the collapsing of both tubes is extremely small.

Owing to the parallel resistors a current flows continuously through

![Diagram](image-url)
the load and the line voltage stays a little below the supply voltage. The repetition frequency is also influenced because of the longer charging time.

A thyratron is well suited for a line pulser as shown by the experiments made. It has a relatively small time jitter, a short deionization time and it is capable to handle high voltages and currents. It can be triggered accurately by a medium-large pulse and because there is no bias necessary, the trigger circuitry has been simplified. A disadvantage could be the impossibility of generating pulse amplitudes lower than a certain value owing to the minimum needed anode voltage to start ionization.

5 THYRISTORS IN LINE TYPE PULSERS.

A thyristor is the solid state version of a thyratron. It is a bistable element with three electrodes: the anode, cathode and the gate. It behaves like a switch with high impedance in the off-state and has a low impedance during the conducting or on-state. In the blocked state only a small forward off-state current flows through the device. When the thyristor conducts, then the on-state current is primarily limited by the impedance of the external circuit. The holding voltage across the device during the conducting period is slightly increased when the current through the thyristor rises. The thyristor stays in the on-state until the current is lowered below a certain holding current.

If the voltage source is not capable to deliver this amount of current, the thyristor returns to its high impedance state, as is the case in a line pulser after the discharging of the line. The magnitude of the break-over voltage of a thyristor can be varied by injection of carriers at the gate. After applying a trigger pulse of sufficient magnitude to the gate, the thyristor starts to conduct very fast. The on-state voltage is slightly higher than the voltage drop of a semiconductor diode. Due to the small area of the thyristor pellet where current conduction starts to flow after the triggering, the amount of current that can be handled in the early period of conduction is limited. So a high voltage drop across the device exists during the first few hundred nanoseconds after the triggering which determines the power dissipated in the thyristor. The di/dt rate of the on-state current is increased for larger values of the gate current and determines the shape of the current pulse through the thyristor and the turn-on time to reach a certain current.
A critical value of the off-state voltage-time rate \((dv/dt)\) must not be exceeded to prevent spontaneously conducting. Owing to the slow charging of the line this value will not be achieved when a thyristor is used in a line pulser. The repetition frequency will be limited mainly by the gate recovery time and the dissipated power. To achieve short turn-on times it is important to trigger the thyristor with relatively large pulses.

5.1 SOME EXPERIMENTS WITH 2N3525 THYRISTORS.

The RCA 2N3525 thyristor is a medium-voltage, medium-current, fast thyristor for use in power control and switching applications.

In Fig. 28 is schematically shown the use of this thyristor in a single and in a series operation mode to deliver positive output pulses. The maximum forward blocking voltage of the device is 600 V.

With the pulser of Fig. 28a an output of about 295 V into 50 ohm and a rise time of 200 ns can be achieved if a trigger signal of 10 V height and 1 us width is supplied to the thyristor. Because the output pulses are slow, no special care in the lay-out is needed.

The resistors parallel to the thyristors in Fig. 28 b and c, have to divide the high-tension equally over the switches. Due to these resistors the line voltage will be lower than the supply voltage, because a current keeps flowing through \(R_c\) when the line has already been charged.

A pulse transformer has been used to trigger the thyristors simultaneously. These transformers are 1:1 types, but also devices with more than one secondary winding on the same core can be used.

With the double-thyristor circuit a maximum output of 580 V with 140 ns
rise time has been achieved when the supply voltage was 1300 V.

The triple-thyristor pulse generator achieves a maximum output of about 800 V into 50 ohm.

The indicated curves of Fig. 29 show the output voltage and the rise time of the pulse as a function of the supply voltage for this last-named pulser. As a result of the large rise time, no further experiments have been carried out with thyristors, although better results may be achieved when thyristors are used with a higher di/dt rate.

In spite of the bad rise time these thyristor generators are quite useful for trigger applications. The single thyristor version gives already a sufficient trigger signal to start ionization in a thyratron.

In section 7 a few fast-switching thyristors will be indicated.

6 AVALANCHE TRANSISTOR PULSE GENERATORS.

It would be outside the scope of this report to give a detailed description of the avalanche process which occurs in most switching transistors. Sufficient literature is available dealing with this subject e.g. see the references 9 to 16 in this report.
In the reverse biased collector-base junction of such a transistor only a small saturation current flows as long as the voltage is well below the breakdown point. Increasing of this voltage will rise this off-state current a little, until breakdown occurs which is due to impact ionization. Minority carriers which have been generated thermally, diffuse to the high-field region of the junction and will be accelerated. Owing to collisions with the atoms of the lattice, hole-electron pairs will be produced which on their turn generate other carriers.

This process results in a suddenly increase of carrier concentration and the current which will be allowed to flow through the transistor is only limited by external circuit conditions. The voltage across the transistor will collapse to a low value.

The property of the transistor to present a negative resistance to the external circuitry is useful to switch relatively large currents in very short times.

Before breakdown occurs only a small current will flow through the transistor so this could be seen as an opened switch while the low resistance \( r_i \) during the avalanche period approaches a closed switch.

The static \( V_{CE-IC} \) characteristic of an avalanche transistor for a certain value of \( I_B \) is shown in Fig. 30. The breakdown occurs at a voltage a little lower than the value \( V_{CBO} \).

6.1 AVALANCHE PULSER WITH A CAPACITIVE COLLECTOR LOAD.

The capacitor \( C \) charges through a high resistance \( R_c \) connected to the supply voltage (Fig. 31). Two kinds of operation are possible: free run and triggered operation.

In the free run mode, the slope of the static load line \( \frac{1}{R_c} \) and the value of \( V_B \) has to be chosen to intersect the breakdown point \( A \), where also the dynamic load line...
intersects the \( V_{CE} - I_C \) curve. When the voltage on \( C \) rises, it reaches the value \( V_A \) and the transistor avalanches. \( I_C \) increases abruptly until it has the value corresponding to the semi-stable point \( B \) (the intersection of the dynamic load line and the \( V_{CE} - I_C \) curve).

Both current and voltage remain there until the capacitor has been discharged so far that the current at \( B \) no longer can be maintained, so the working point travels downwards the curve until the current reaches \( I_H \) (point \( C \)), where the dynamic load line just touches the curve. A further discharge is impossible and the avalanching stops. As the static load line was chosen not to intersect the region of negative resistance, conduction ceases and the working point travels to \( D \). The capacitor will then be allowed to recharge and the cycle repeats.

Fig. 32 shows the voltage across \( R_o \) and on the collector in the case of

a) a capacitive collector load
b) with a storage line.

6.2 PULSER WITH A STORAGE LINE.

If a line is used as the collector load instead of a capacitor, a fast-rising rectangular pulse can be produced. There are no reflections if the sum of the load resistance and the effective resistance of the avalanche transistor equals \( Z_0 \) of the line as is shown in Fig. 32b.

About half the voltage difference \( V_A - V_H \) is available for the output pulse (if \( r_f \) is not too large) and the pulse width is determined by the length of the line.

The switching process is the same as described for a capacitive load.

In both cases the pulse generator may be triggered by choosing the static load line not to intersect the avalanche point but at a slightly lower value of \( V_{CE} \). This can be done either by increasing \( R_C \) or decreasing \( V_B \) or \( R_B \).

To trigger the transistor a small positive pulse must be supplied either to the base or to the collector of the transistor to start the avalanching.

To achieve the shortest possible rise time and delay, the method with collector triggering must be used. Besides the working point has to be
chosen as close as possible to the avalanche point.
The pulse generator as shown in fig. 31 delivers a positive pulse. The
reversed polarity will be achieved when the load resistor is placed in
serie with the capacitor or in the earth connection of the line.
The maximum repetition frequency will be determined by the average
dissipated power in the transistor.

6.3 SELECTION OF AVALANCHE TRANSISTORS.

To examine if a particular transistor (npn) has a sufficient voltage
drop, the circuit of Fig. 33 may be used. The pulse generator must be
capable to deliver voltage pulses up to 200 V with a width of 50-100
us and a repetition rate of 100 Hz. A thyristor equipped pulser is
quite suitable because the rise
time of the pulse preferably must
not be shorter than a few psec.
The display on the oscilloscope
screen will show the heavy drawn
parts of the $V_{CE-I_C}$ curve from
Fig. 30. When the scales have been
calibrated, it is possible to read immediately the values of $V_A$, $V_H$, $I_A$
and $I_H$ for particular values of $R_C$ and $R_b$ from the screen.
If pnp transistors have to be examined the polarity of the generator
pulse must be reversed. The screen now shows the $V_{CE-I_C}$ curve in the
third quadrant.
To deliver high output voltages, transistors having a large $V_A-V_H$ must
be selected.

6.4 EXPERIMENTS

In this section a survey is given of some experiments which have been done
with two avalanche transistors namely the 2N914 and 2N697.

6.4.1 Avalanche transistor 2N914.

Six samples have been tested in a way as described in 6.3 and the results
have been tabulated. For a description of the symbols see Fig.30.
The results have been achieved with $R_b=10$ Kohm. Increasing of the
external base to emitter resistance gives a decrease in $V_A$, $V_H$, $I_H$ and $I_A$. 
The sample No.1 has been used in a capacitive loaded pulser in which $R_c = 100$ Kohm, $R_b = 10$ Kohm, $R_o = 50$ ohm, $C = 100$ pF and $V_B = 65$ V.

An output pulseform was achieved as indicated in Fig. 32a, with a rise time of 0.6 ns, a width of 15 ns (10 p.c. points) and a height of 28 V.

When the supply voltage was increased to 300 V, the pulse repetition frequency became 500 KHz.

Also an experiment has been done by changing the capacitor by an air-line of 1.5 m length. The observed pulse had a rounded leading corner and 3 steps were clearly visible at the trailing edge when the pulser was terminated with 50 ohm (= $Z_o$). $R_o$ has to be lowered to 20 ohm before a rectangular pulseform was achieved. The rise time was 450 ps, the amplitude 8 V (into 20 ohm) and the duration was about 10 ns.

The other samples also could be brought to avalanche. From these measurements it could be concluded that the effective switch impedance during the avalanche period was about 30 ohm for a 2N914 transistor.

### 6.4.2 2N697 transistor in an avalanche pulser.

Ten samples have been tested and each of them show to give a voltage drop between 70 and 80 V. The following experiments were made

a) An avalanche transistor pulse generator has been constructed as indicated in Ref. 10, where three 2N697 transistors in a series connection have been used, to achieve a 2 ns output pulse of 150 V into 50 ohm. Although we used the same transistor type (SGS-Fairchild) we could not obtain these specifications. The rise time was 25 ns and some changes in resistance values had to be made before the three transistors started to avalanche. Perhaps better results could be obtained when transistors from another manufacturer are used.

b) The scheme of Fig. 31 has been used to build a pulser with a capacitive loaded collector. The results are tabulated on page 32.
<table>
<thead>
<tr>
<th>C (pF)</th>
<th>R_o (ohm)</th>
<th>V_o (V)</th>
<th>t_r (ns)</th>
<th>width (ns)</th>
<th>f (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>200</td>
<td>80</td>
<td>14</td>
<td>80</td>
<td>40.10^3</td>
</tr>
<tr>
<td>1000</td>
<td>120</td>
<td>15</td>
<td></td>
<td>600</td>
<td>1.10^4</td>
</tr>
<tr>
<td>1.10^4</td>
<td>130</td>
<td>15</td>
<td></td>
<td>8.10^3</td>
<td>4.10^3</td>
</tr>
<tr>
<td>100</td>
<td>50</td>
<td>13</td>
<td></td>
<td>34</td>
<td>8.10^4</td>
</tr>
<tr>
<td>1.10^3</td>
<td>75</td>
<td>25</td>
<td></td>
<td>200</td>
<td>1.10^4</td>
</tr>
<tr>
<td>1.10^4</td>
<td>100</td>
<td>25</td>
<td></td>
<td>5.10^3</td>
<td>4.10^3</td>
</tr>
</tbody>
</table>

V_B = 150 V, R_c = 47 Kohm, R_b = 470 ohm, V_{trig} = 10 V, C_{in} = 3.9 nF.

c) An avalanche transistor trigger amplifier.

Fig. 34 shows the scheme of a trigger pulse generator, which can produce 5 μsec pulses with an amplitude of 110 V into 50 ohm and a rise time of 40 ns. The maximum repetition rate at full output is about 400 Hz and an input pulse of 3 V is sufficient.

![Trigger Amplifier Circuit Diagram](image)

This amplifier is used to trigger the earlier described thyratron pulser. An external trigger signal starts the avalanching process of the first stage. The collector voltage is well below the breakdown value in the off-state of the transistor. This stage produces 36 V pulses in the primary winding of a 1:1:1 pulse transformer.

The in series connected transistors of the second stage have also been adjusted below breakdown by means of a suitable value of the supply voltage, R_c and the two bleeder resistors.

The lumped constant network provides in a rectangular pulse shape, and the emitter resistor prevents unloaded operation.

7 CONCLUSION.

In this report a description has been given of a few line-type pulse generators. The results can be summarized in a table to obtain a good survey of the properties of the particular pulse generators.(only single switch pulsers terminated with 50 ohm are considered)
# Type pulser | $V_o$ | leading edge | rise time | top | ripple | max. freq. \\
| M.W.C.R. | up to 2.5 KV | clean | 375 ps | flat first | 120 Hz | 
| CLARE | up to 1.0 KV | | 250 | | ns | 100 | 
| HAMLIN | | | | | | 
| Thyatron | FX2513 | | 18-23 ns | small | > 5 KHz | 
| | 7190 | | 15-21 ns | | > 5 KHz | 
| Thyristor | 2N3525 | | 200 ns | none | > 5 KHz | 
| Avalanche transistor | 2N697 | | 13-25 ns | not | rect | typical | 80 KHz |

**REMARK 1:** The scheme of Fig. 35 gives a suggestion to double the repetition frequency of mercury relay pulser, in which both stationary contacts have been used. Two equal lengths of cable are needed.

**REMARK 2:** To improve the rise time of thyatron pulsers, tubes with shorter ionization times have to be used.

In Ref. 8, a 20 KV pulse generator with 2 ns rise time has been described.

**REMARK 3:** An improvement of the thyristor pulser will certainly be obtained if a Motorola 2N4204 or MCR 729-10 fast switching thyristor is used. These devices have a $di/dt$ rate of 5 A/ns.

**REMARK 4:** To improve avalanche transistor pulsers, fast switching transistors have to be selected with high $V_A - V_H$ values. Series operation is possible (see Ref. 9, where an output of 80 V into 50 ohm has been obtained with a rise time shorter than 1 ns.)

8 **ACKNOWLEDGEMENTS.**

The discussed pulse generators form a part of the scientific instruments used at the Department of Electrical Engineering, to investigate properties of solid state microwave devices.

The author thanks Ir. Th. G. van de Roer for his helpful suggestions and for reading the manuscript. The mechanical parts have been constructed under the supervision of Mr. H. Treur.
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APPENDIX 1

List of special components.

Mercury wetted relays ———— RP5441 C.P. CLARE. International N.V.
  ———— HRC-1 Tongeren, Belgium.
Thyratrons ———— 7190 Hamlin, Flight Refuelling L.T.D.
  ———— FX2513 Industrial Electronics Div.
  ———— C.P. CLARE. International N.V.
Avalanche transistors ———— 2N914 Tung-sol, Bloomfield, New Jersey, U.S.A.
  ———— 2N697 English Electric Valve Co. L.T.D.
  ———— C.P. CLARE. International N.V.
Delay lines ———— RG 218/U Amphenol and Alpha Wire.
  ———— HF 5/8" Kabelmetal, Communications Div.
  ———— C.P. CLARE. International N.V.
High-Voltage capacitors ———— DD60 Centralab- Globe Union.
High-Voltage connectors ———— HN Amphenol.
Bifilarly wound chokes ———— Potcore Philips P45/25,3B5,u=200.
  for heater decoupling 2x28 turns of en.cop. wire 1.2 mm Ø
  L=0.8 mH (without d.c. current.)
or
  ———— 2x100 turns of en.cop. wire 1.2 mm Ø L=18mH
  (without dc current) on EI 84/32 core.
  ———— air-gap 0.25 mm.
Pulse transformers ———— 1:4 turns ratio: core Ferroxcube 3El green.
  Core material: Philips.
  Shape: torus
  0.D. 35.5 mm, I.D. 22.5 mm
  height 9.8 mm
  prim. 25 turns, sec. 100 turns of isolated
  wire 0.5 mm Ø.
  — 1:2 turns ratio: same core. prim. 25 t.
  sec. 50 t.
  — 1:1:1 t.ratio : same core. 3x25 turns.
  — 1:l t.ratio : core 3El, 0.D 23 mm, I.D. 14mm
  height 7 mm. prim. 20 t. sec. 20 turns.
Tube connections of the applied thyratrons.

FX2513 7190

APPENDIX 2.

THE DESIGN OF LUMPED-CONSTANT TRANSMISSION LINES.

On page 6, already a remark was made on the application of lumped-constant transmission lines in a line pulser to generate long pulses. The use of an equivalent length of coaxial cable is too expensive and also unmanageable. A number of variations are possible in the design of such lines. Because of its relatively easy construction an asymmetrical line was designed composed of several \( n \)-sections as shown in the scheme below (without the dashed resistors). Theory about this subject can be found elsewhere.

Some important formulae for a lossless line are

\[
Z_{on} = \sqrt{\frac{L}{C}} \frac{L}{1 - \omega^2/\omega_c^2}, \quad \text{in which } Z_o = \text{characteristic imp. of a line section}
\]

\[
\omega_c = \text{cut-off frequency}
\]

\[
L = \text{serie inductance of } 1 \text{ section}
\]

\[
C = \text{shunt capacitance , , , , ,}
\]

If \( \omega \ll \omega_c \) then \( Z_{on} = \frac{1}{\omega C} = Z_o \). The delay for \( n \)-sections is given by \( t_{dn} = \sqrt{\frac{L}{C}} \cdot n \) and the rise time by \( t_{rn} = 1.1 \sqrt{n \sqrt{L} \sqrt{C}} \).

The calculated data for a few lines (\( Z_o = 50 \, \text{ohm} \)) are given in the table.

<table>
<thead>
<tr>
<th>delay(ns)</th>
<th>rise-time(ns)</th>
<th>cut-off freq.</th>
<th>L (( \mu \text{H} ))</th>
<th>C (pF)</th>
<th>number of sections</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>27</td>
<td>( 1.10^8 )</td>
<td>0.5</td>
<td>200</td>
<td>15</td>
</tr>
<tr>
<td>500</td>
<td>130</td>
<td>( 2.10^7 )</td>
<td>2.5</td>
<td>1000</td>
<td>10</td>
</tr>
<tr>
<td>1000</td>
<td>260</td>
<td>( 1.10^7 )</td>
<td>5.0</td>
<td>2000</td>
<td>10</td>
</tr>
<tr>
<td>2200</td>
<td>520</td>
<td>( 4.5.10^6 )</td>
<td>11.0</td>
<td>4400</td>
<td>10</td>
</tr>
</tbody>
</table>
The correct value of the capacitors was obtained by selection and parallel connection of commercially available high-voltage capacitors (Centralab, type DD60). The inductors have been wound on potcores and the value is adjusted by a ferroxcube rod in the centre hole. All cores have an internal air-gap, adjusted by the manufacturer (Philips).

150 ns line: potcore P 11/8, 3.5 turns of en. copper wire 1 mm \Ø
500 ns : P 18/11, 4
1 μs : P 18/11, 5.5
2.2 μs : P 26/16, 9
extra external airgap of 0.5 mm

After assembling the line on an epoxy substrate a reflection and a transmission measurement has been carried out with a T.D.R. to determine the pulse response of the line.

It appeared that a large reflection occurred at the input and output terminals of each line. The display of the reflection curve in the case of the 500 ns line is shown below. An air-line between the T.D.R. and the line represents the reference level and the open end of the line is terminated.

The large dip which occurs after the step is due to the first capacitance of the first section. The impedance curve of the line is far from ideal especially during the first 300 ns. When the line was used in a line pulser, a pulse with large overshoot and ringing was generated. To improve the reflection characteristic and still using the mounted coils and capacitors, a few resistors have been placed across some components in the first section (see page 36). The value of the resistors is determined experimentally by observing the oscilloscope display and it appeared that a nearly ideal reflection curve could be obtained.
This is shown in the following two curves which refer to the same line. Now the impedance-distance function is a straight line except for a small reflection at the input of the line due to the connection leads of the coil and the capacitor. It could not be decreased appreciable.

All lumped lines were treated in this way at both terminals. However, the use of these damping-resistors increases the rise time of the line with a factor 1.5 and makes the line more dissipative. Using this line in a line pulser, a flat pulse without overshoot or ringing could be obtained. A limitation was set to the maximum pulse height as a consequence of the application of potcores. Above certain voltages, the pulse shape slowly deteriorated and the impedance of the line increased. The maximum pulse height for a particular line is:

- 150 ns line: up to 2 KV
- 500 ns line up to 1 KV
- The 1 us and 2.2 us line can be used up to 500 V.