An Analog System for the Design of Switched Discharge Circuits in Plasma Physics

G. Herppich, A. Knobloch

IPP 4/29 April. 1966

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ABSTRACT:

In designing pulse discharge circuits it is necessary to have a cheap and quick method of checking the computed data.

This is afforded by the switching circuit analog system. A method was devised in which the ordinary switches, i.e. spark gaps or ignitrons of the original arrangement, are replaced by mercury-wetted contacts. These are operated by a program controlled system with special terminal amplifiers. The program controlled system enables the switches to be delayed from 0 ... 1000 μs. With the aid of the special terminal amplifiers the jitter of the relay is limited to ± 300 ns.

With a linear impedance transformation the real and distributed electrical values will be transformed in such order of magnitudes that they can be easily maintained and adjusted. The models are operated at low voltage.

The model investigations are carried out mainly in original time scale. In investigating circuits with transit time effects, this approach has the advantage of allowing original components (e.g. cables or sandwich conductors) to be used.

The capacitor-bank models are set up quickly and conveniently by means of pin boards designed for this purpose. These enable a maximum of six batteries in crowbar operation to be plugged in.

In the case of single-switch models it is possible with a sampling oscilloscope to obtain unique and rapid actions on the screen in the form of steady images.

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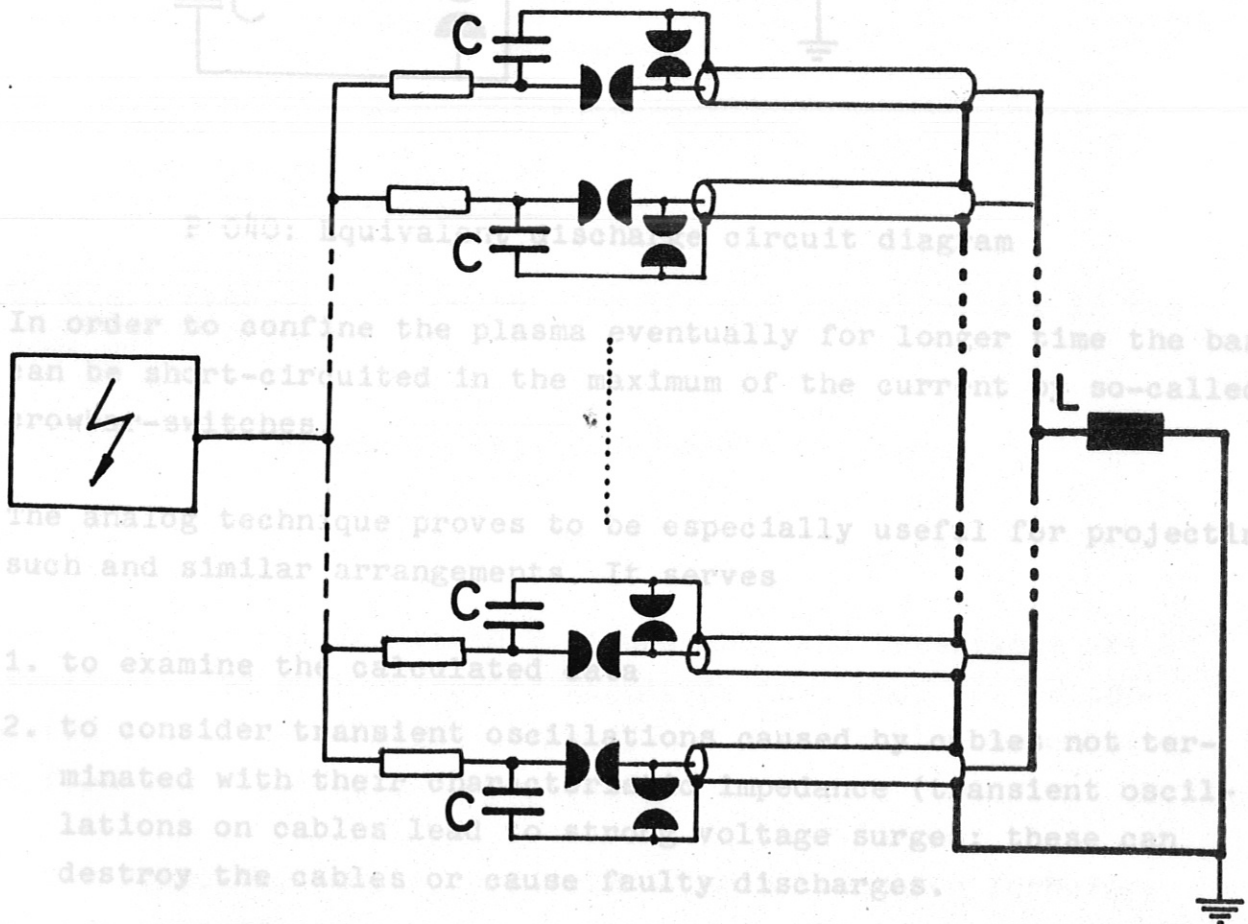
1. Reason for using switched analog circuits

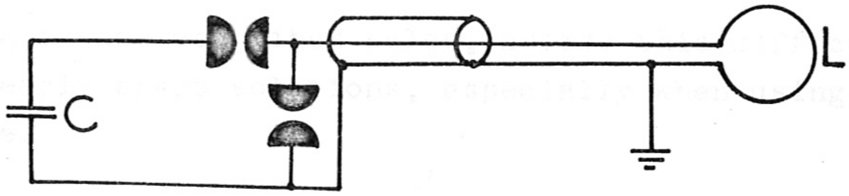
Most of the discharge circuits used in plasma physics for producing very hot plasma by means of quick compression, are built up similar to the discharge circuit shown in P 039.



P 039: Discharge circuit

A magnetic field which rises from 0 to approx. 10^5 gauss within a few microseconds is produced in a usually single turn coil. In order to achieve the correspondant current rise the discharge circuit has to be built with very low inductance and low damping.

A high energy efficiency demands that only a small part of the total circuit inductance is in the bank. This requires a great number of parallel circuits.



P 040: Equivalent discharge circuit diagram

In order to confine the plasma eventually for longer time the bank can be short-circuited in the maximum of the current by so-called crowbar-switches.

The analog technique proves to be especially useful for projecting such and similar arrangements. It serves

1. to examine the calculated data
2. to consider transient oscillations caused by cables not terminated with their characteristic impedance (transient oscillations on cables lead to strong voltage surges; these can destroy the cables or cause faulty discharges.
3. to examine a required current program, especially with respect to cooperative effects (in systems where different banks are connected with a common load, e.g. bias field bank, preionization bank, main bank).
4. to find out the conditions for producing given pulse shapes by time-delayed switching of several active and passive circuits.
5. to simulate non-electrical systems with the aid of electrical analog circuits (spring-mass vibration systems, e.g. collector of pulse current arrangements).

Analog computers being found on the market are not very appropriate for the treatment of such problems because they require mathematical preparations of the problem solution. In addition the solution is only approximate in the case of lines being involved.

The analog method described below, avoids this difficulty and enables nearly exact solutions, especially when using a real time scale.

2. Low-voltage analog models

The electrical data of pulse circuits are approximately in the range of:

characteristic impedance	<1 ohm
inductance	<100 nH
rise time	~ 10 ns

The values of the capacitance, inductance and resistance are transformed in such orders of magnitude that they can be connected quickly and easily as handy and purchasable components to form the required switch-circuit.

In the following chapter two sets of transformation formulars will be resumed:

1. a linear impedance-transformation with transformed time scale
2. a linear impedance-transformation with real time scale

2.1 Transformed time scale [1,2]

For linear impedance transformation the following equation is valid:

$$\vec{Z}(\omega) = b\,\vec{Z}\left(\frac{\omega}{a}\right)$$

where a is the ratio of model time over real time

$$a = \frac{t_m}{t}$$

and b the ratio of model impedance over real impedance

For the impedance components one has

$$R_m = bR$$
$$L_m = abL$$
$$C_m = \frac{a}{b} C$$
$$\omega_m = \frac{1}{a} \omega$$

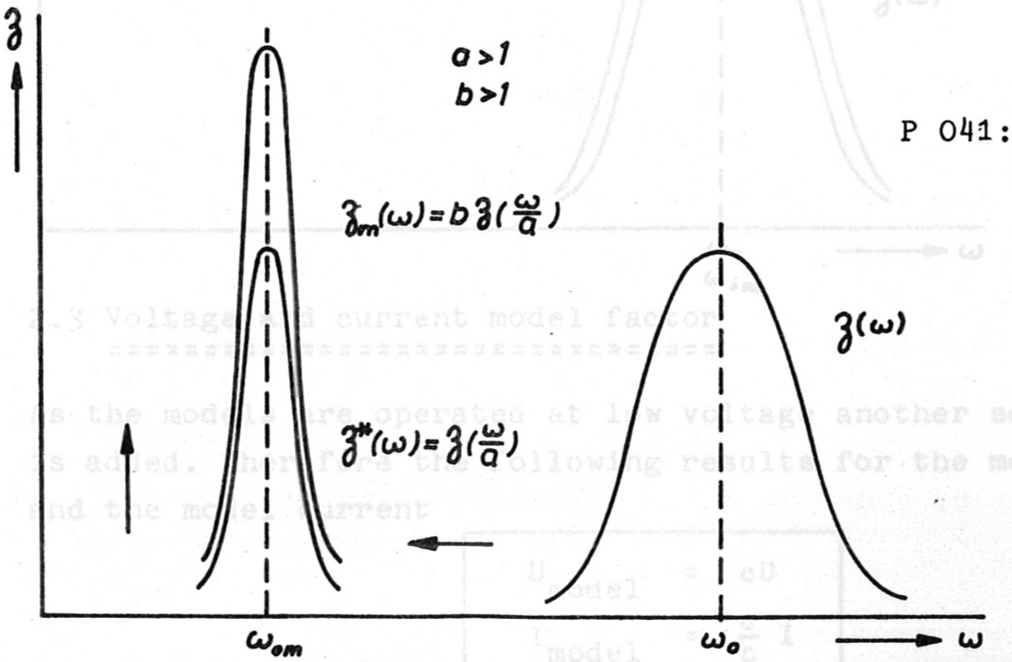
which means for the characteristic impedance (without losses)

$$Z_m = bZ$$

and for the circuit Q

$$Q_m = Q$$

Picture P 042 gives the impedance for a resonant circuit versus frequency and shows the influence of the transformation factors a and b



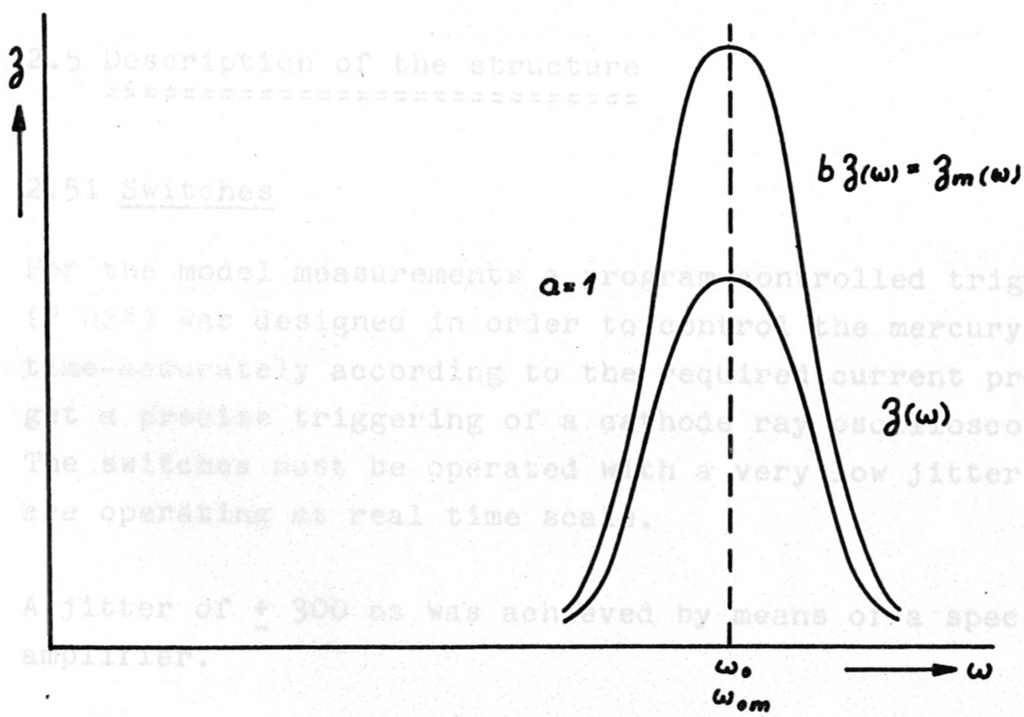
P 041: Time-impedance transformation

2.2 Real time scale

The list of transformation equations for a = 1 is

$$Z_m = bZ$$
$$L_m = bL$$
$$C_m = \frac{1}{b} C$$
$$R_m = bR$$
$$Q_m = Q$$
$$t_m = t$$

Picture P 041 shows the influence of the transformation factor b with a = 1



P 042: Real-time-impedance transformation

2.3 Voltage and current model factor

As the models are operated at low voltage another scaling factor is added. Therefore the following results for the model voltage and the model current

$$U_{model} = cU$$
$$I_{model} = \frac{c}{b} I$$

2.4 Aspects for the choice of the analog system

The choice of the analog system is dependant on the time scale chosen. The model with real time scale has the advantage of being able to represent the transients on original components (cable, sandwich conductor). By using this type of model the construction of approximate delay lines with concentrated components becomes unnecessary. The real time scale demands a switch whose rise time is roughly identic with the rise time of an original switch (spark-gap or ignitron). The mercury-wetted contact relay is suited for this purpose.

Several problems demand single switch models. Here the model with real time scale is always preferred as the jitter does not play any part.

2.5 Description of the structure

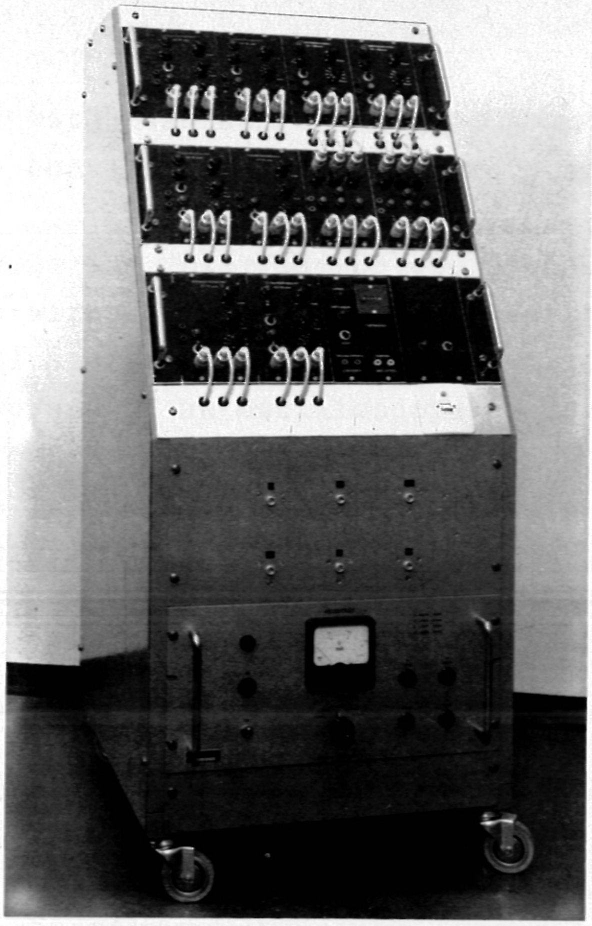
2.51 Switches

For the model measurements a program-controlled trigger apparatus (P 024) was designed in order to control the mercury switches time-accurately according to the required current program and to get a precise triggering of a cathode ray oscilloscope. [3, 4, 5, 6]. The switches must be operated with a very low jitter as the models are operating at real time scale.

A jitter of $\pm$ 300 ns was achieved by means of a special terminal amplifier.

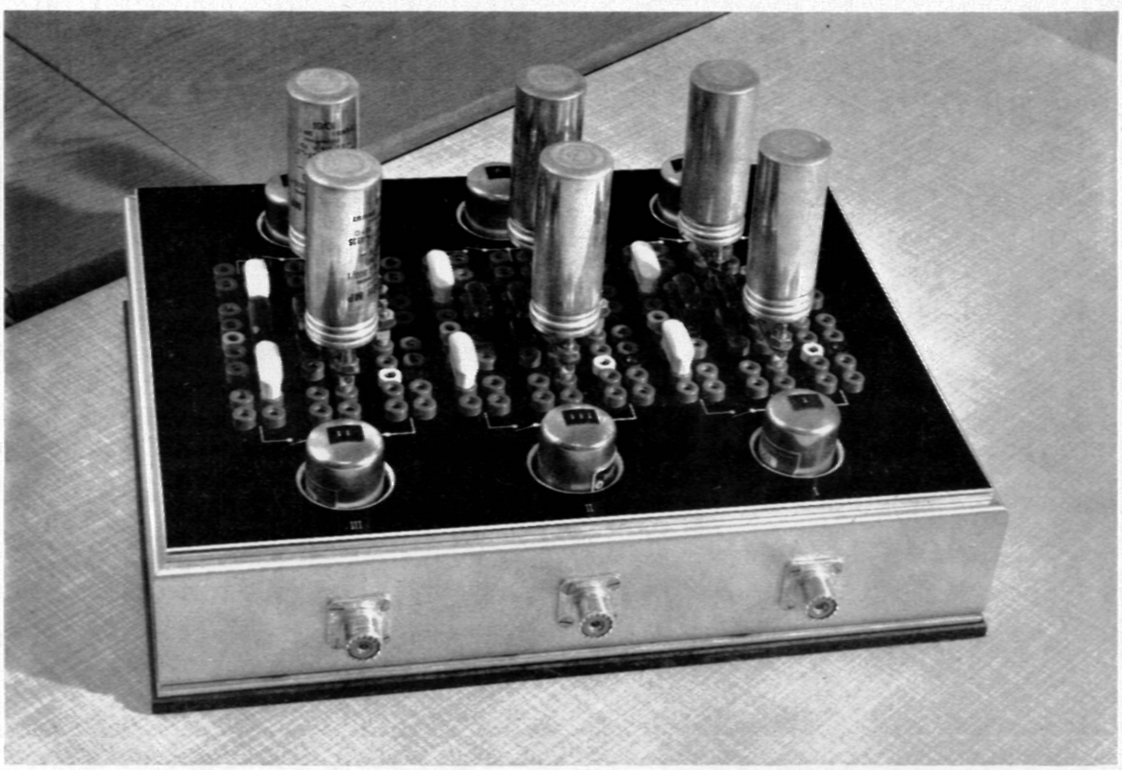
The mechanical mercury switch, used here, has the advantage of

1. being bounce-free
2. having a low ohmic resistance and being able to connect relatively high peak currents.



P 024 Switching Analog System

Program controlled trigger device
for 6 mercury wetted relays



P 025. Switching Analog System

Pinboard for 6 circuits

Models were operated with peak currents of 15 A and more without destroying any relay contacts or causing sources of error.

In single switch models the relay may be operated directly by the line voltage (50 Hz) without amplifier. This has the advantage that the examined voltages and currents of the switch circuit can be obtained on the screen of an oscilloscope as steady images.

The second advantage is the fact that very rapid processes, as transients, can be examined by use of sampling oscilloscopes.

2.52 Pin boards

Standard pin boards have been developed for building up the model switch circuit quickly and well-arranged. These boards allow to plug a maximum of six switch circuits very quickly (P 025).

There are also pin boards where coaxial cables with different diameters can be clamped to the switch circuit.

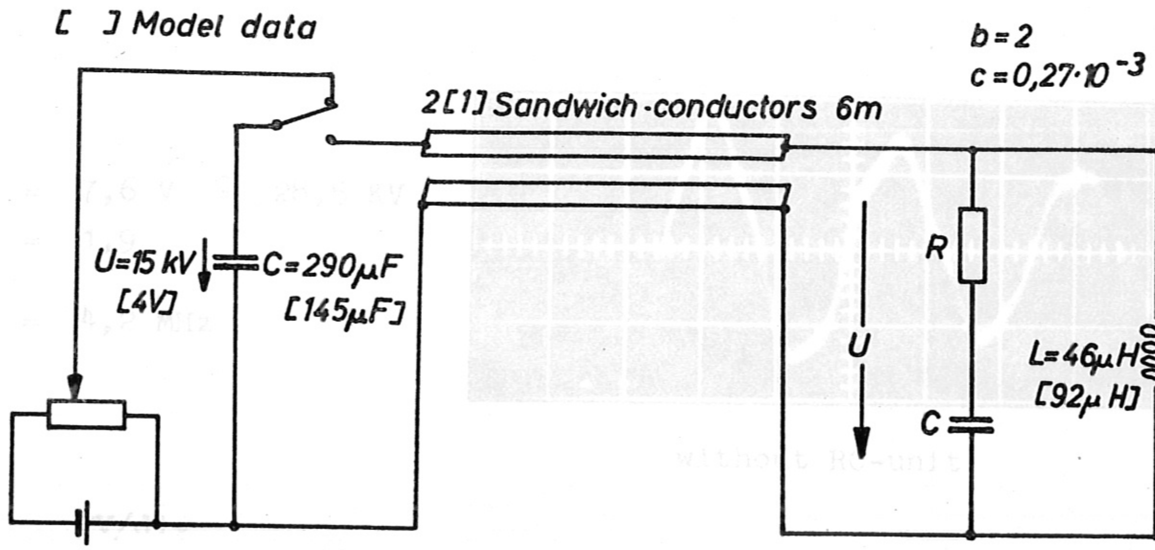
Air-core coils as inductances, ceramic tubular capacitors and small trimmer resistors as plug units are auxiliary equipment.

3. Application of the model system

3.1 Single-cable model: Determination of an RC matching unit for a bias field bank (according to picture P 043).

The ratio maximum voltage at the end of the load line over charging voltage must not be higher than 1.45.

An RC matching unit connected in parallel to the load, has to be designed in order to attenuate the load line to a certain extent.



P 043: Equivalent circuit diagram of the bank including the model data

In this case the load line consists of 2 sandwich conductors. Thus the model factor is b = 2.

It turns out practical to choose the model factor always equal to the number of single circuits of a bank.

Picture P 043 shows the original and model data. An original sandwich conductor is used in the model.

The results of the model measurement are to be seen in picture P 026.

Optimizing the matching unit data led to model data of

$$R_m = 18.5\Omega; \quad C_m = 3.3 \text{ nF}$$

which means for the original unit

$$R = 9.25\Omega; \quad C = 6.6 \text{ nF}$$

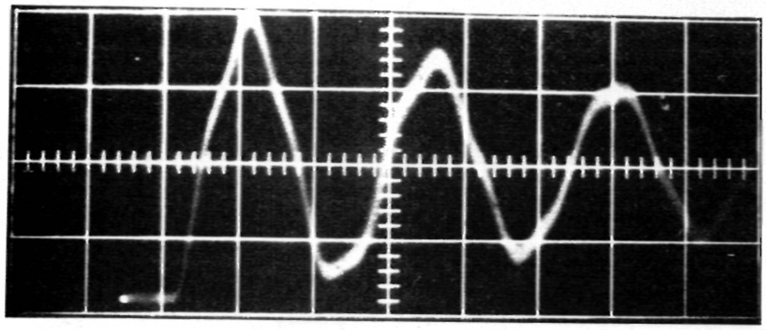
P 026

Suppression of voltage reflections by RC-matching units

$\hat{U} = 7{,}6\ V \ \hat{=}\ 28{,}5\ KV$

$\frac{\hat{U}}{U} = 1{,}9$

$f = 4{,}2\ MHz$



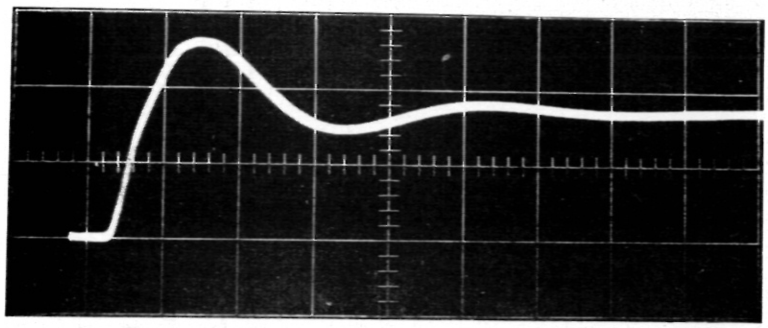
without RC-unit

2V/div

0,1 μs/div

$\hat{U} = 5{,}2\ V \ \hat{=}\ 19{,}5\ KV$

$\frac{\hat{U}}{U} = 1{,}45$



with RC-unit

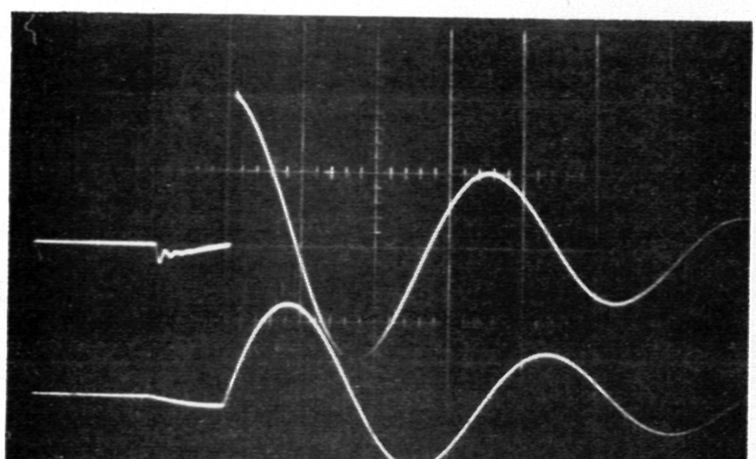
P 039

Model-voltage and model-current of the 2.6 MJ-bank

5 V / div

5 A / div

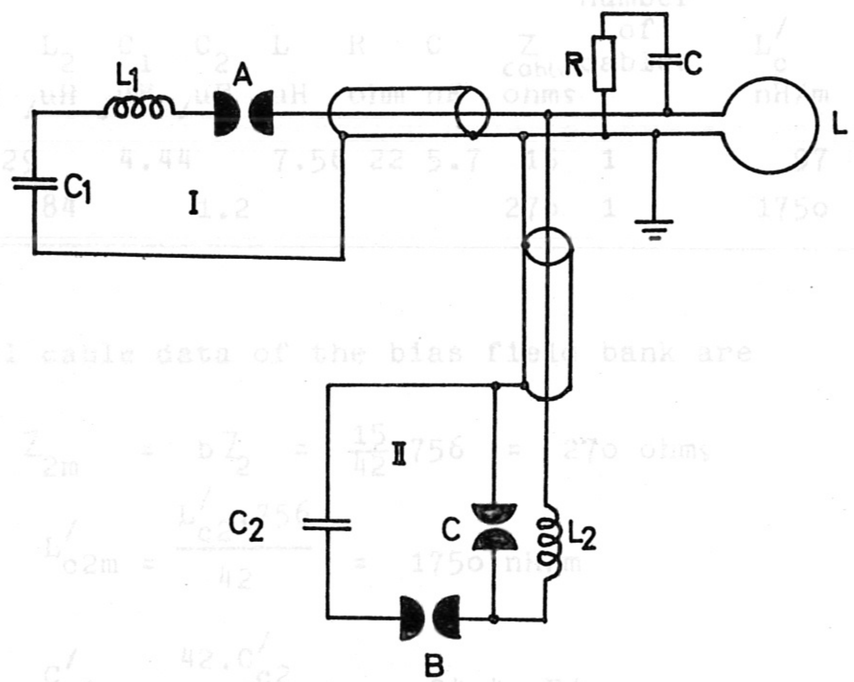
10 μs / div



3.2 1.5/2.6 MJ bank Isar I

3.21 Equivalent circuit diagram

The bank has the following equivalent discharge circuit diagram:



P 044: Equivalent circuit diagram

The bank consists of a main- (I) and a bias field bank (II). A special voltage- and current program in the coil was required in order to produce a dense plasma.

The original data are listed in the following table:

bank	L_1 nH	L_2 nH	C_1 μF	C_2 μF	L nH	R mΩ	C μF	Z cable Ω	number of cables	L'_c nH/m	cable data C'_c pF/m
I	1.7		336o		10	0.029	4.32	15	756	97	44o
II		111		92o				15	42	97	44o

- 1o -

3.22 Model of the 1.5/2.6 MJ bank

One original cable is used in the model for the main bank which means b = 756.

The data of the model are listed in the following table:

bank	L_1 /uH	L_2 /uH	C_1 /uF	C_2 /uF	L /uH	R ohm	C nF	Z_{cable} ohms	number of cables	L'_c nH/m	cable data C'_c nF/m
I	1.29		4.44		7.56	22	5.7	15	1	97	44o
II		84		1.2				27o	1	175o	24.4

The model cable data of the bias field bank are

$$Z_{2m} = b Z_2 = \frac{15}{42} 756 = 27o \text{ ohms}$$

$$L'_{c2m} = \frac{L'_{c2} \cdot 756}{42} = 175o \text{ nH/m}$$

$$C'_{c2m} = \frac{42 \cdot C'_{c2}}{756} = 24.4 \text{ pF/m}$$

A cable which had approximately the required data, was taken.

In the model a charging voltage of 10 v was chosen.

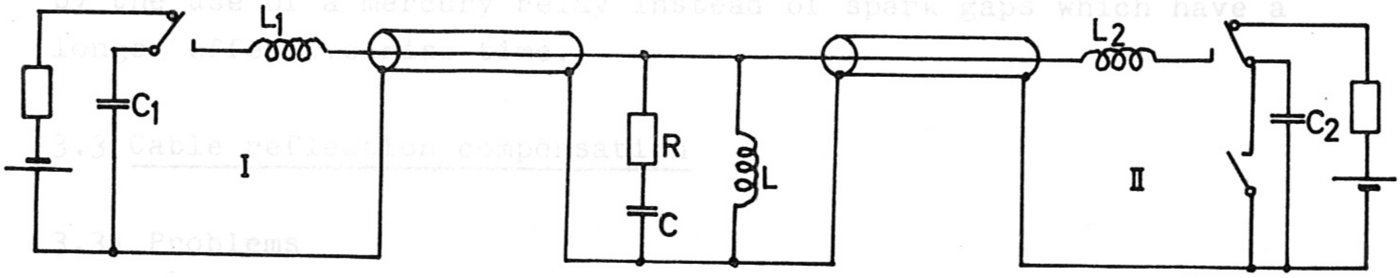
Therefore one has

$$c = \frac{1o\text{v}}{4o\text{kv}} = 0.25 \cdot 10^{-3}$$

and for the evaluation of the oscillogramm

$$I = \frac{b}{c} \cdot I_{model} = 3.15o \cdot 10^{6} \cdot I_{model}$$

P 045 shows the circuit diagram of the analog model.



P 045: Analog model of the 2.6 MJ bank
with bias field bank

Measurement results:

At first the bias field bank II is connected to the load L over a cable with a current rise time of 10 /us. The crowbar circuit of the bias field bank is closed by the switch C when the current has reached its maximum.

About 10/us after the start of bank II the main bank I is discharged also with a rise time of 10/us.

P 039 shows this program in the form of the model voltage and current loops.

Comparison of model- and original measurements:

	Values measured on the model	values measured on the original
Frequency $f/_{kHz}$	25	24.25
Reversal %	82	81.5
$\frac{U}{U_{25kHz}}$ ratio of peak load voltage over main frequency load voltage	1.54	1.25

The values are in good accordance; only the surgevoltage is higher in the model than in the original. This can partially be explained by the use of a mercury relay instead of spark gaps which have a longer effective rise time.

3.3 Cable reflection compensation

3.31 Problems

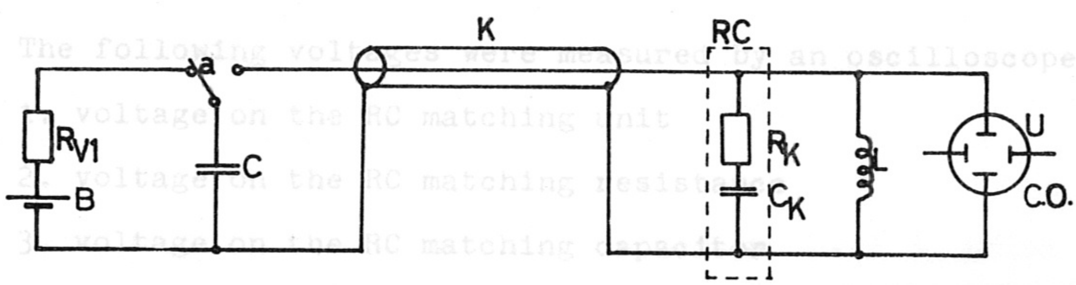
Usually in the discharge circuits of capacitance banks the energy is being connected to the load over coaxial cables. The cables cannot be properly matched because of the inductive load. Therefore a part of the energy is reflected at the end of the cables and runs back and forth. This causes overvoltages on the cables which can lead to distructions.

During the construction of the 1.5/2.6 MJ bank it was found that the overvoltages can be strongly reduced by RC matching units at the end of the cables.

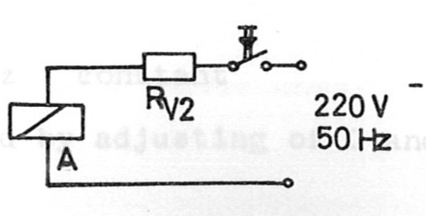
The optimum RC matching unit was determined for two types of cables used in the IPP (described in the article IPP 4/51, G. Herppich which will shortly appear). The following is part of this report:

Matching of a 40 kv cable (4o P3) for a discharge frequency of 25 kHz and cables lengthes of l = 2 - 15 m.

Picture P 046 shows the model circuit.



P 046: Model circuit



A = Clare Relay HG 1004

B = charging battery

C = charging capacitor

C_k = matching capacitor

R_k = matching resistance

K = cable 40 P3

L = load impedance

R_{v1}/R_{v2} = resistance

U_1 = charging voltage

The capacitor C is charged over contact a. If the relay is switched on, the capacitor C will be discharged over the cable K and the load coil L.

Measurements:

The optimum compensation of the reflection is determined with different RC matching units.

For constant values of C_k R_k has to be changed until an optimum is produced.

The optimum compensation is defined by

1. minimum of the number of oscillations

2. the rise of the voltage has not to be influenced

The following voltages were measured by an oscilloscope:

1. voltage on the RC matching unit

2. voltage on the RC matching resistance

3. voltage on the RC matching capacitor

Parameters

Cablelength l = 2 - 15 m; f = 25 kHz = constant

The discharge frequency was obtained by adjusting of C and L.

3.33 Results:

For interpretation of the oscillograms

$\hat{U}$ = maximum voltage

U_f = maximum voltage of the extrapolated fundamental wave

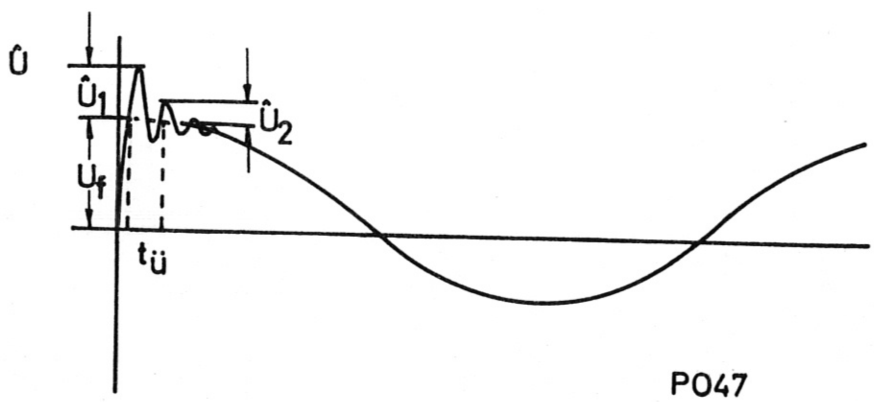
I_k = maximum current in the compensation matching unit

U_c = voltage on the compensation capacitor

U_R = voltage on the compensation resistance

U_L = charging voltage

The maximum voltage is competant for the stress of the cable termination. The voltage relations were drawn as curves in dependance of the compensation capacitance.



P047

Examples for the derivation of RC matching unit values

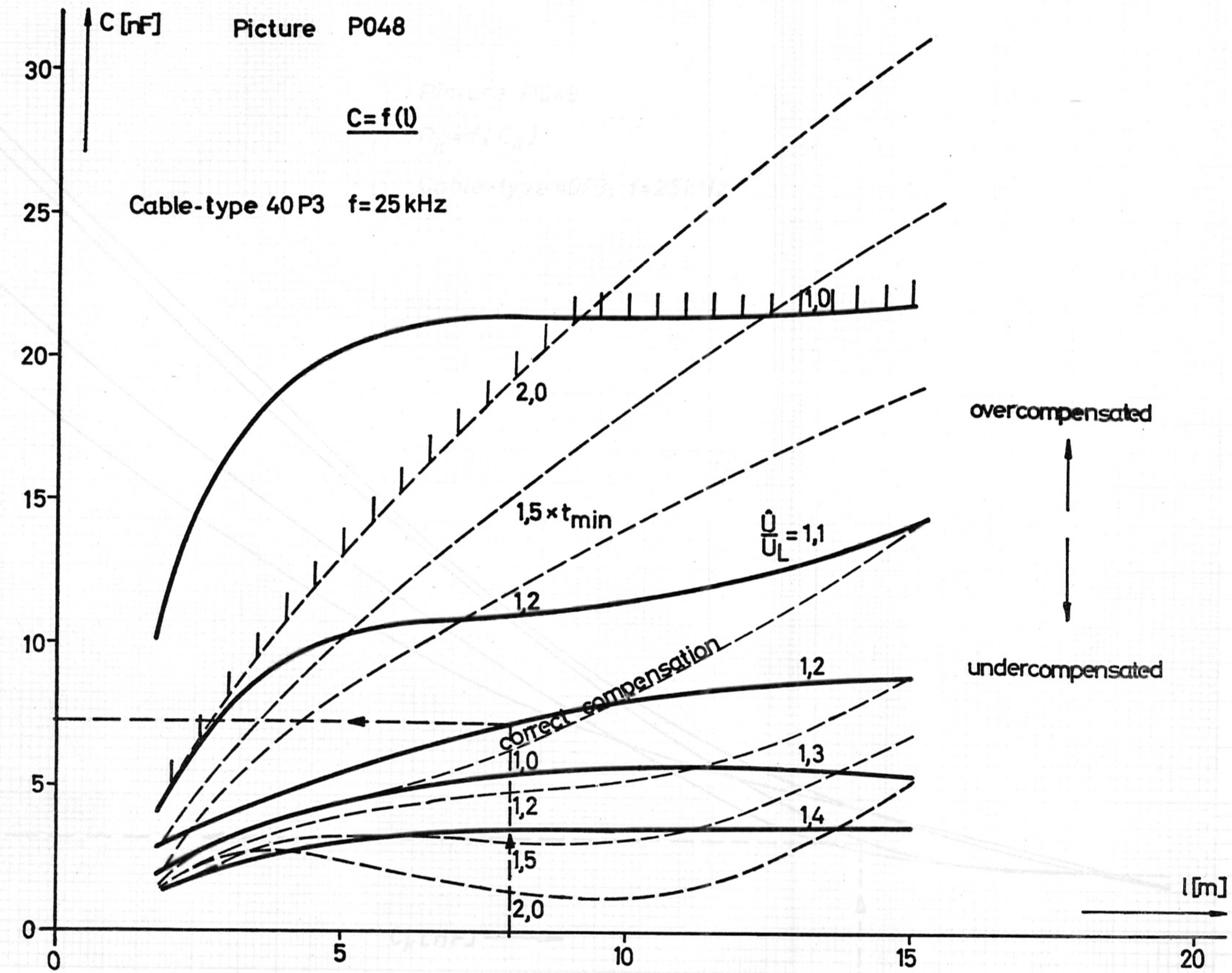
For a pulse bank with 4o cables (cabletype 4o P3 with an average cablelength l = 8m) the optimum RC matching unit values are to be found. The ratio peak voltage over charging voltage shall not be higher than 1.2.

One finds from picture P 048 C = 7.3 nF for 8 m, which in turn from picture P 049 gives R = 16.7 ohms. As the curves hold for one cable, the data for the bank are

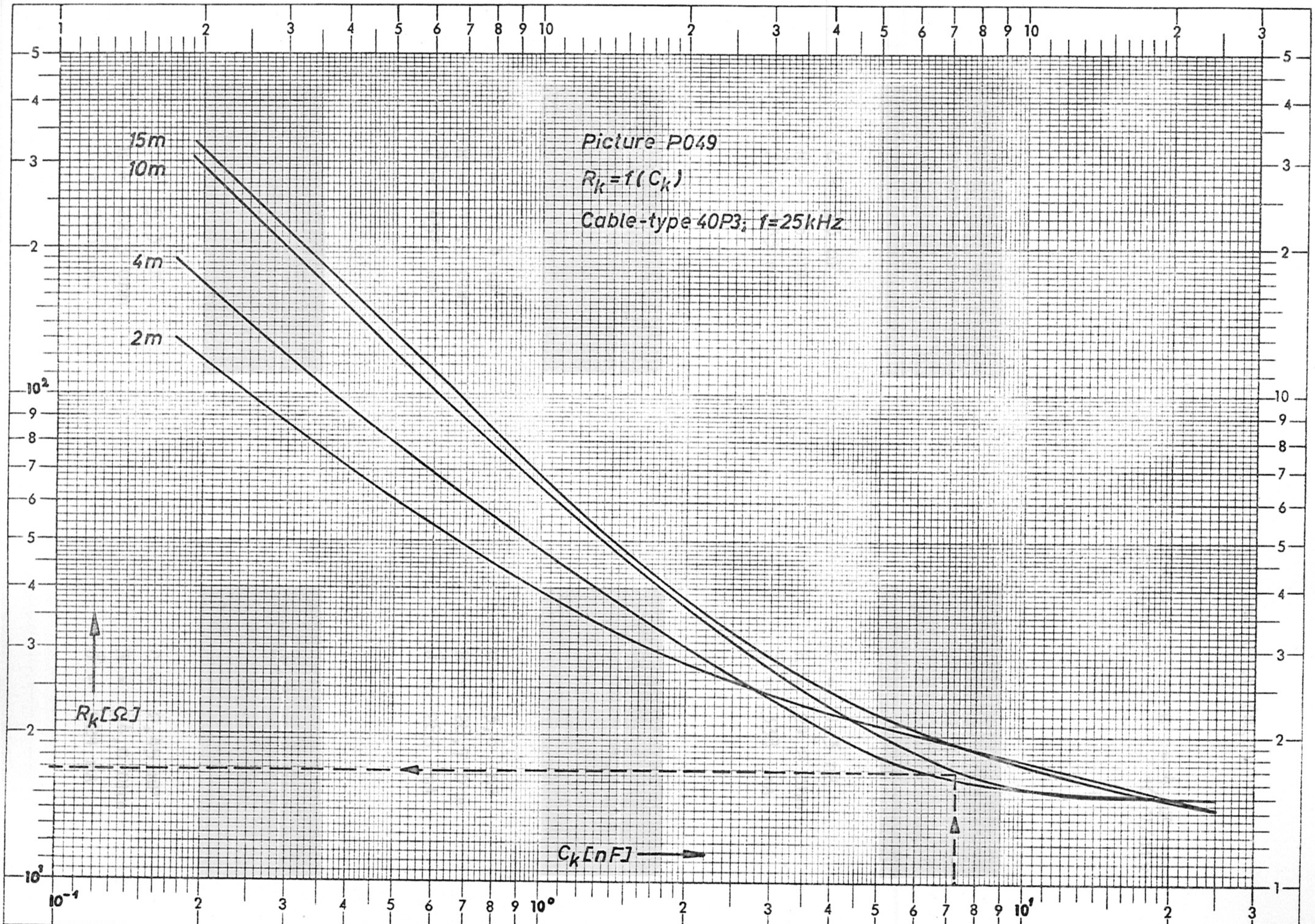
$$C = 0.292\ \mu F; \quad R = 0.418\ \text{ohms}$$

In addition one sees from picture P 048 that in this case the damping of the transients is nearly optimum.

This work was performed under the terms of the agreement on association between the Institut für Plasmaphysik and EURATOM.



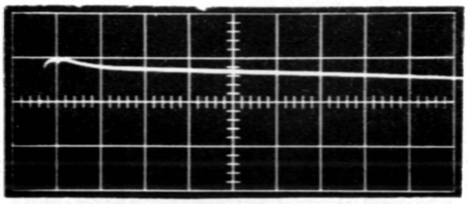
C [nF]
Picture P048
C= f (l)
Cable-type 40 P3 f= 25 kHz
30
25
20
15
10
5
0
5
10
15
20
l [m]
1,0
2,0
1,5 × t_min
1,2
Û/U_L = 1,1
correct compensation
1,2
1,0
1,2
1,3
1,4
1,5
2,0
overcompensated
undercompensated



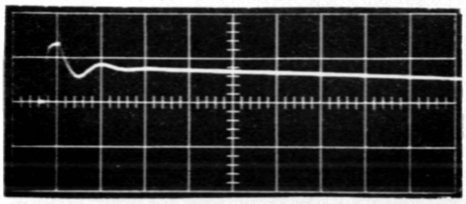
Beide Achsen logar. geteilt, 1 bis 300 u. 1 bis 50, Einheit 100 mm

P 027 Voltage on the RC-Matching Unit (U_{RC})

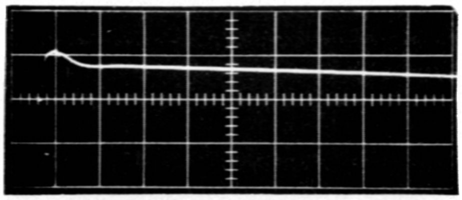
Cablelength l = 15 m
f = 25 kHz C = 4 uF
0,5 us/div 10 V/div



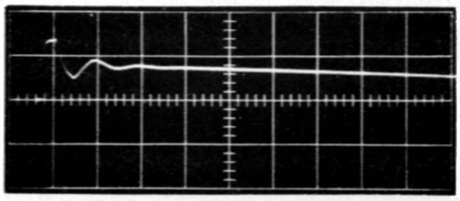
C = 23 nF
R = 15 Ohm
$\hat{J}$ = 533 mA



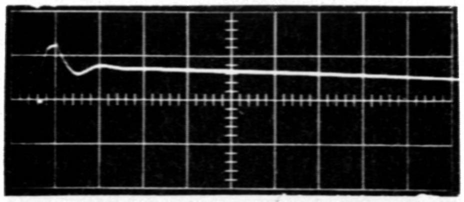
C = 4,3 nF
R = 24,2 Ohm
$\hat{J}$ = 338 mA



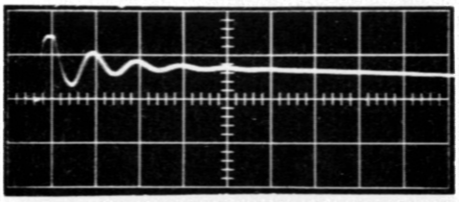
C = 11,4 nF
R = 17,5 Ohm
$\hat{J}$ = 457 mA



C = 3,0 nF
R = 28,7 Ohm
$\hat{J}$ = 286 mA



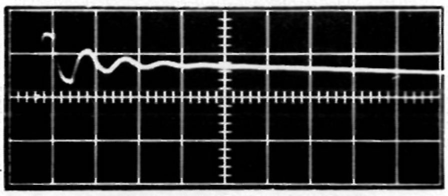
C = 5,3 nF
R = 22,5 Ohm
$\hat{J}$ = 356 mA



C = 2,45 nF
R = 34,0 Ohm
$\hat{J}$ = 224 mA

P 028

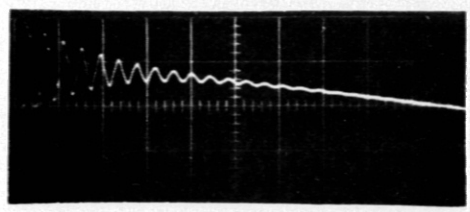
0,5 µs / div
10 V / div



C = 1,7 µF
R = 59 Ohm
$\hat{J}$ = 159 mA

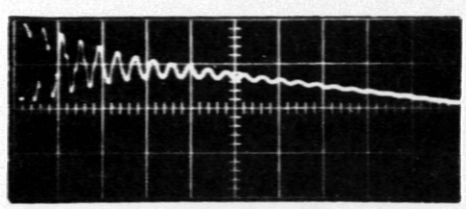
C = 445 pF
R = 156 Ohm
$\hat{J}$ = 67 mA

C = 0,83 µF
R = 77 Ohm
$\hat{J}$ = 125 mA



C = 21o pF
R = 288 Ohm
$\hat{J}$ = 35 mA

C = 0,58 µF
R = 126 Ohm
$\hat{J}$ = 83 mA



C = 97 pF
R = 500 Ohm
$\hat{J}$ = 20 mA

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