ON THE TRANSMISSION OF SIGNALS BY THE WIDE BAND PICK-UP STATION

by H. H. Umstätter

1. Introduction and Summary

When studying the interaction between beam and accelerating cavity, one wants to know the true shape of proton bunches in particular at transition energy and distinguish it from signal distortions caused by the pick-up station itself. During the last PS shutdown (May 1967) the wide band P.U. station has been taken out of the ring and its signal transfer function (amplitude and phase) measured up to 600 MHz with a reflectometer bridge. These data have been introduced into a computer programme "RESPONS" *) which calculates and plots how a given signal of the bunch shape is transmitted and distorted by the wide band pick-up station (connected to MCR). These results may help other users of the pick-up station to avoid misinterpretations of the observed signals of bunch shapes. The effect of signal transmission through 150 m of cable type A from the ring to the MCR has also been considered. Finally, a Chebyshev low-pass filter is proposed to suppress ringing.

2. Measurements in the laboratory

The vacuum tank from straight section 92 with both wide band P.U.-electrodes (MCR and CB) and attached sections of 0.95 m elliptic vacuum chamber have been set up in the central building, and a 1 mm wire extended along the center axis to transmit test signals similar to previous measurements [1] except that a thinner wire has been used. If a short current pulse $\int I dt$ is sent into the wire, this pulse travels with its associated TEM wave along the wire with the

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*) Modified version of programme M1 in the MPS programme list.

velocity of light in a similar way as the charge of a bunch of protons travels in the accelerator.

The electrical field around a charged wire inside a cylindrical conductor can be conformally mapped on the field inside a nearly elliptic boundary by the function

$$x + iy = \text{ar}\tanh(u + iv)$$

Fig. 1 illustrates this field. The plot in fig. 1 has on top a scale indicating the electrostatic potential around a uniform line charge inside the vacuum chamber of the PS and has a vertical scale on the left indicating the mean diameter of these equipotential lines. By dividing this "potential per line charge density" by the velocity of the signals ($3 \cdot 10^8$ m/sec) one obtains the characteristic impedance of the transmission line consisting of wire and vacuum chamber (scale on the bottom). The transmission line*) has been matched on the far end by a resistor and on the near end by a minimum loss attenuator (L-pad) which is also matched to the 75Ω cable which carries the input signal.

Transmission of sine waves: The signal from the generator was split into two parts by means of a matched T: one entering the vacuum chamber via the minimum loss attenuator, the other going through an attenuator into the reflectometer bridge ("Z-g-diagraph" from Rohde & Schwarz) where its amplitude and phase are compared with the output signal of the wide band pick-up station (pick-up electrode + cathode follower).

If one writes the input current in the vacuum chamber in the form $I_0 e^{j\omega t}$ then the output voltage of the pick-up station can be written

$$V = T(\omega) \cdot I_0 e^{j\omega t}$$

where the complex factor T is the transfer function. Its modulus $|T|$ is plotted in fig. 2. The logarithm of T is plotted in fig. 3

$$\log \frac{T}{T_0} = \alpha(\omega) + j\varphi(\omega) \qquad T_0 = 4.8 \text{ V/Amp}$$

*) characteristic impedance is kept constant by variation of the wire diameter corresponding to the diameters of vacuum tank and vacuum chamber.

where α is the attenuation and φ the phase lag (α is plotted in decibels and φ in degrees). These are the actual readings taken on the Z-g-diagraph.

One can see in fig. 2 that the pick-up station transmits signals of even more than 400 MHz, but the frequency response is not flat and the sensitivity is overcompensated for high frequencies. There are several minima at approximately equal frequency intervals (at 150, 270, 400, 527 MHZ) which indicate standing waves on the pick-up electrode and the amplifier circuit. In addition there is a sharp minimum at 485 MHZ. It can be seen more clearly in fig. 3 which shows that also the phase is shifted by 360° (from 463 to 505 MHZ). Perhaps the pick-up station was better in the past.

The circuit of the amplifier is shown in fig. 4. At low frequencies it works as a cathode follower, but at high frequencies the cathode follower is bypassed by the 15 pF capacitor and 33 Ω resistor which transmit the signal from the electrode directly to the matched cable. However, stray capacities and inductances make the actual circuit more complicate. Therefore we limit ourselves to regard the pick-up station as a black box of which we know only the transfer function. These measurements have been made with small signals (P.U. station output < 20 mV) so that nonlinear effects are excluded. Unfortunately, due to an error in a circuit drawing the amplifier was supplied with 150 V instead of 210 V dc. This may change the tube characteristics but not the circuit elements and geometry of the electrode. It is hoped that this did not deteriorate much the behaviour of the P.U. station. It must also be remembered that higher modes may exist in the vacuum tank beyond 600 MHz which are outside the range of the instrument*).

3. Calculated transmission of bunch shapes

Bearing in mind the mentioned restrictions we shall now use the available measurements to study on the computer how various bunch shapes are transmitted by the pick-up station under test conditions. The data of fig. 3 have been punched on cards and read into the computer programme "RESPONS" which calculated and plotted the following examples by Fourier transformation.

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*) In particular a 640 MHz oscillation with high Q value can be observed after short bunches with the 1000 MHz oscilloscope [2],[6].

First a triangular bunch of 6.4 nanosec length is assumed to travel in the vacuum chamber. This is the bunch length observed at transition energy in the PS in 1965[2]. Fig. 5 shows the corresponding output pulse after the cathode follower of the wide band pick-up station. (The pulse height and t = 0 have been chosen arbitrarily).

Note: 1. The transmitted pulse is a triangle with a rounded top and the bunch length extrapolated to the base line is unchanged (6.4 nsec) by bandwidth limitations.

2. About 6 nsec after the bunch follows a small negative bump and a bit later a smaller positive bump. These seem to be reflections: The signal picked up by the electrode (elliptic cylinder) enters the amplifier circuit where it is delayed and partly reflected with negative polarity by some capacity representing a low impedance at high frequencies. Then the signal goes back through the vacuum seal, travels around the circumference of the electrode and returns to appear as an attenuated negative bump. After a further reflection it should appear as a smaller positive bump.

3. A tail of 5 oscillations/10 nanosec of decreasing amplitude follows. It corresponds to the 485 MHz resonance in fig. 2,3. The sharper the peak on top of the bunch, the more it excites this oscillation. One might expect that this "ringing" depends on the bunch repetition frequency, but calculations for bunches at 9.413 MHz (transition) and 9.5 MHz repetition rate yielded almost the same result as for a single bunch, so that it is not worth reproducing these results.

4. Before the triangular output signal of the pick-up station arrives, one observes a slow rise of the voltage which is due to the pick-up station and should be disregarded when reading the bunch length.

Fig. 6 shows how a triangular bunch of 10 nsec length is transmitted: Since the charge is the same, the pulse height is smaller and one can see better the triangular shape. Less ringing is observed, and the negative reflection is weaker, because it overlaps partly the bunch itself.

Fig. 7 shows how a |cosine| -pulse of 10 nsec length is transmitted, similar to the bunches in the PS before transition. The bunch shape is transmitted quite correctly and less ringing occurs because the top of the pulse is rounded. The least ringing occurs for a gaussian distribution but this seems not to be the case in the PS.

If the output signal in fig. 5 is transmitted through 150 m of cable type A from the ring to the M.C.R.[3], this has little effect on the bunch shape (fig. 8). It is very important to use few and good connectors (not BNC 75 Ω) and to match the wide band oscilloscope carefully in order to avoid reflections between pannel connector and oscilloscope. A good attenuator should be used to check whether spurious reflections can be attenuated.

4. Signal improvement by a low-pass filter

The programme has also been used to study the effect of simple lossless filters which could be inserted between two matched 75 Ω cables (fig. 9, 10). A low-pass filter could be used to eliminate the 500 MHz oscillation. When choosing between a maximally flat (Butterworth) response and an equal ripple (Chebyshev) response, the latter has been preferred, because one can take advantage of a large ripple to equalize the frequency response of the pick-up station. Such a filter is given in fig. 9 for insertion between two matched 75 Ω transmission lines. (Chebyshev filter prototypes are tabulated for instance in reference [4].) The filter transmits f = 0 and f = 275 MHz and it has 2 db insertion loss at f = 159 MHz and f = 318 MHz. For higher frequencies the insertion loss increases by approximately 18 db/oct. Its transfer function is

$$T(\omega) = \frac{1}{(1-\omega^2 LC) + j\omega\left(RC + \frac{L}{2R} - \omega^2 \frac{RLC}{2}\right)}$$

(R = 75 Ω C = 18 pF L = 0.031 μH)

Fig. 9 shows how the pulse of fig. 5 is corrected by this filter. Another Chebyshev filter (C = 27 pF, L = 0.0317 μH) with 2 db ripple and 196 MHz bandwidth has also been calculated, but it is not worth reproducing the result: The top of the triangle is even more rounded because the bandwidth is smaller. This example indicates that the value of the capacity C = 18 pF may be increased and is less critical than the value of the inductance L = 31 nH.

5. Behaviour of the P.U. station in the synchrotron ring

One may expect a difference between the behaviour of the P.U. station in the preceding small signal analysis (output voltage < 20 mV) and the actual signals of several volts produced by the proton bunches. It is known that the base line floats, if the protons are sharply bunched at transition and the signals become large. In fig. 10 a the beam intensity was $0.95 \cdot 10^{12}$ protons/p, whereas in fig. 10 b less current was injected from the linac, so that only $0.30 \cdot 10^{12}$ protons/p circulated. This means that the grid becomes negatively loaded, either because it attracts negative ions [5] or because grid current flows during signals with a high peak.

Acknowledgement

I should like to thank Mr. H. Fischer for discussions and suggestions as well as Mr. J. Jamsek and Mr. E. Schulte. From the discussions I learned more about previous experiences and tests of this wide band P.U. station designed by R. Kaiser.

REFERENCES

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Memorandum MPS/CO of 4th February, 1964

[4] G. L. Matthaei, L. Young, E. M. T. Jones : Microwave Filters, Impedance-Matching Networks, and Coupling Structures (page 100)
McGraw Hill Inc., New York, 1964

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Ch. 4, figs. 8-10, 11
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MPS Scientific and Technical Staff

APPENDIX

Impedance of the P.U. electrode*) in the tank

It has been mentioned that the elliptical pick-up electrode cannot be considered as a lumped capacity but rather as a distributed capacity with distributed series inductance and resistance or, in other words as a curved parallel strip transmission line with losses. This fact can be shown more detailed by a measurement of the complex impedance of the P.U. electrode in the tank as seen from the araldite vacuum seal, which separates it from the cathode follower. The complex impedance is plotted in the Smith chart in fig. 12 in which the center 1 corresponds to 75Ω .

At 30 MHz the electrode behaves like a capacitor of 37 pF

$$\frac{1}{j\omega C} = \frac{-j}{2\pi \cdot 30\ \text{MHz} \cdot 37\ \text{pF}}$$

because it is small compared with one wavelength, but at 184 MHz it behaves like a quarter wave resonator or series resonant circuit, and at higher frequencies the series inductance prevails. The impedance does not become zero at 184 MHz but only 12 ohm, because the electrode consists of a thin resistive layer on glass support to attenuate reflections. Perhaps the resistivity should be further increased.

The two pick-up electrodes connected with M.C.R. and central building are both placed in the same vacuum tank (inner diameter 0.348 m, length 0.434 m) in straight section 92. It may become a cavity resonator. Therefore a metal diaphragm with an elliptical aperture for the beam (8 x 16 cm) has been inserted (after the measurements of this report), which divides the tank into two smaller chambers. Before insertion of this diaphragm, one could see a "cavity mode" at 560 MHz in the impedance plot in fig 11. Although the elimination of this mode is a small improvement, no significant difference in the signals from the bunch before[2] and after[6] this modification was observed and the 640 MHz oscillation persists. It could be attenuated by the low-pass filter.

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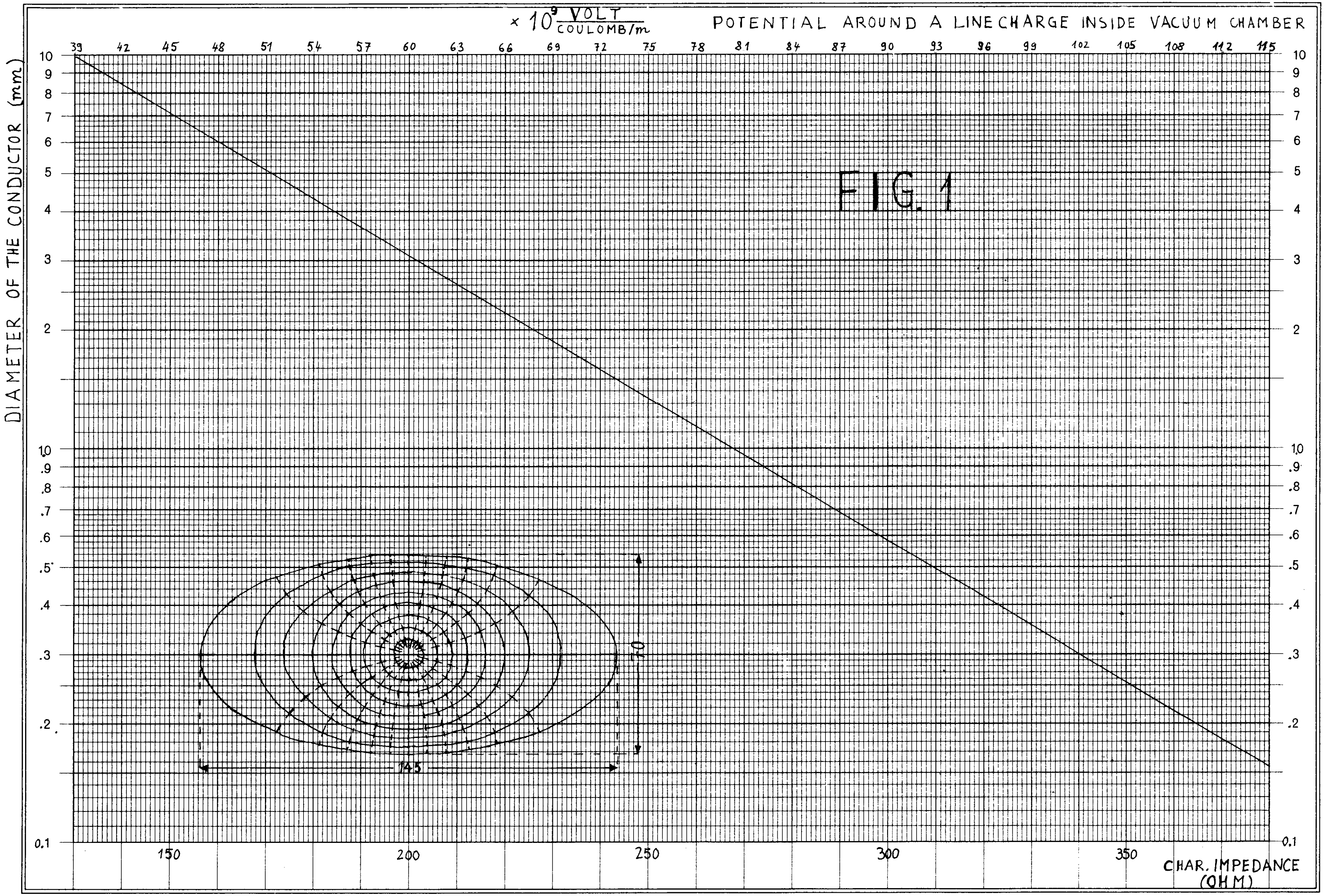
*) This refers to the wide band PU electrode connected to Central building, but both electrodes are similar now.


× 10⁹ VOLT / COULOMB/m
POTENTIAL AROUND A LINECHARGE INSIDE VACUUM CHAMBER
39 42 45 48 51 54 57 60 63 66 69 72 75 78 81 84 87 90 93 96 99 102 105 108 112 115
DIAMETER OF THE CONDUCTOR (mm)
10 9 8 7 6 5 4 3 2
1,0 .9 .8 .7 .6 .5 .4 .3 .2 0.1
FIG. 1
70
145
150 200 250 300 350
CHAR. IMPEDANCE (OHM)

SIS/R/15694

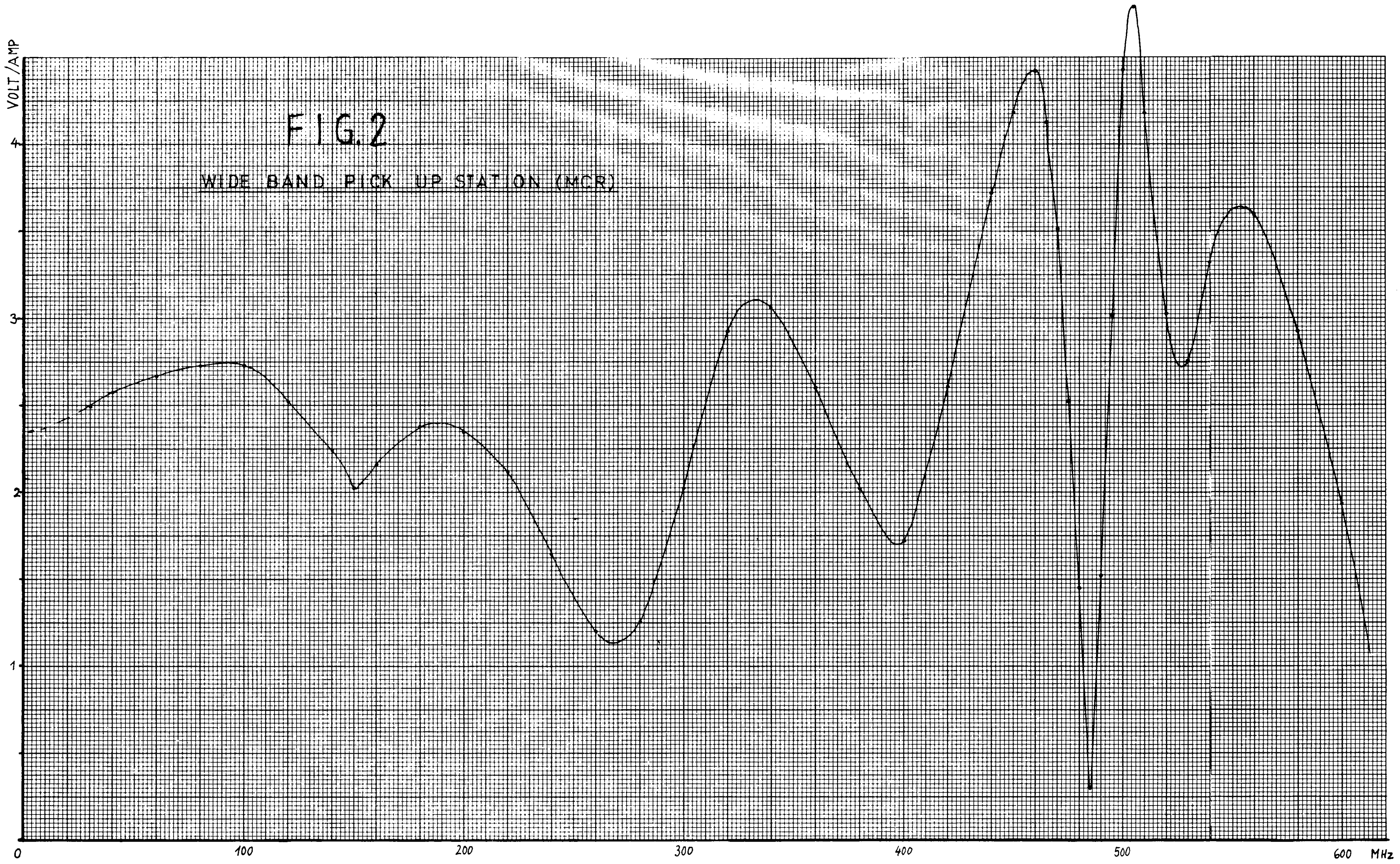


FIG.2
WIDE BAND PICK UP STATION (MCR)
VOLT/AMP
4
3
2
1
0
100
200
300
400
500
600
MHz

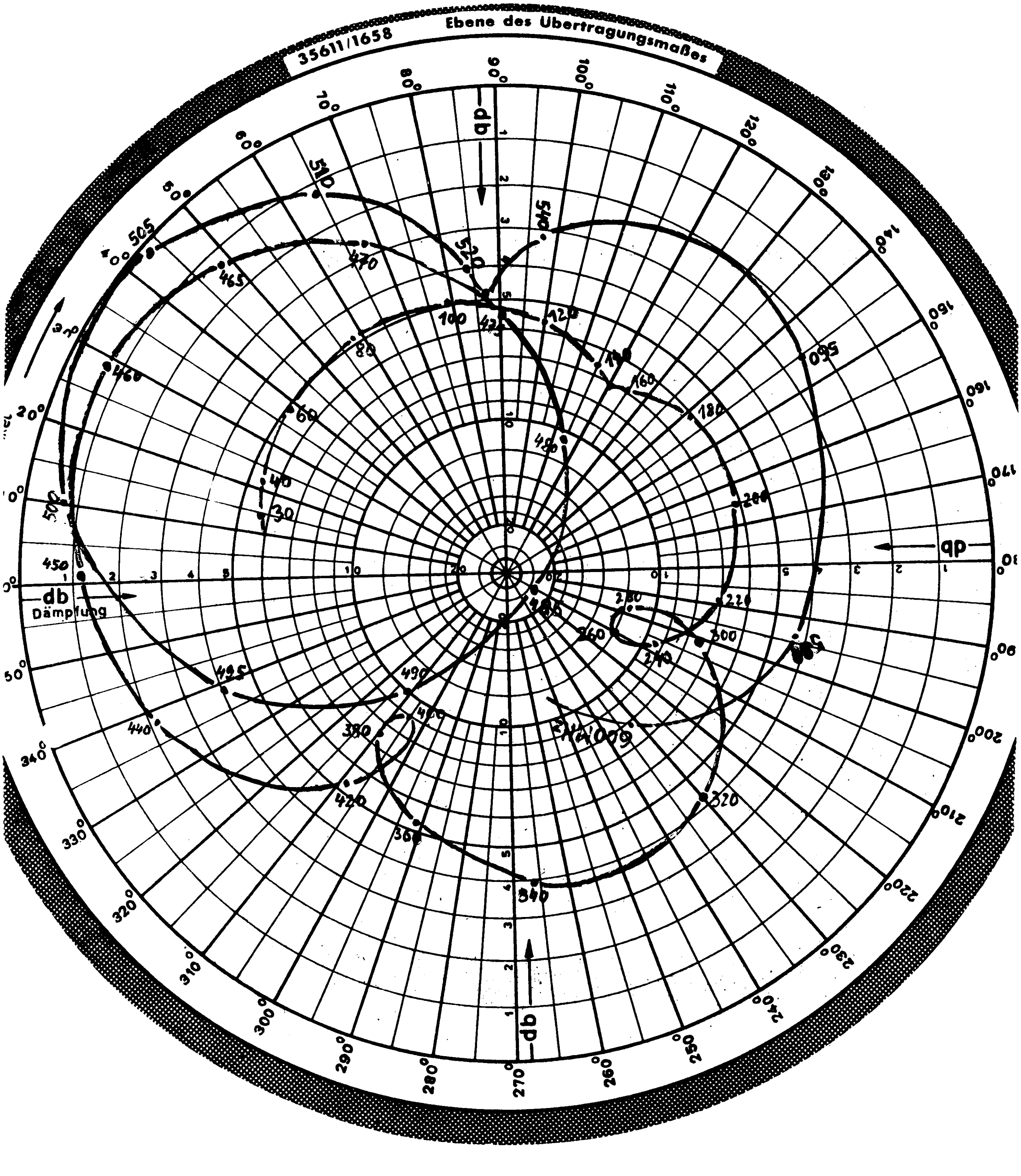

35611/1658
Ebene des Übertragungsmaßes
db
Dämpfung
db
db
db

Fig. 3

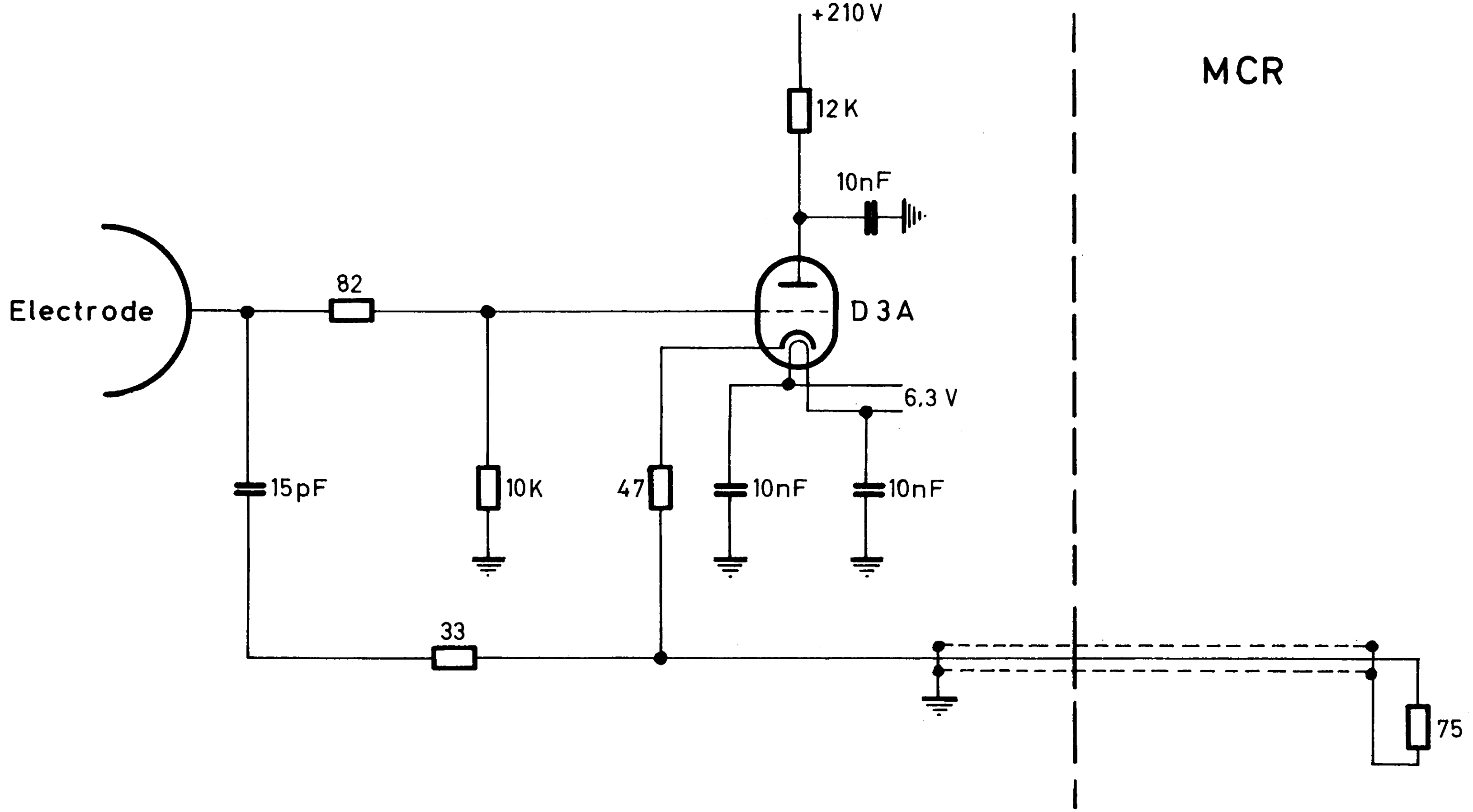


FIG. 4

Wide Band Pick Up Station	CERN - MPS
Head Amplifier	2746
	RF-1-4
	22.10.64 H.

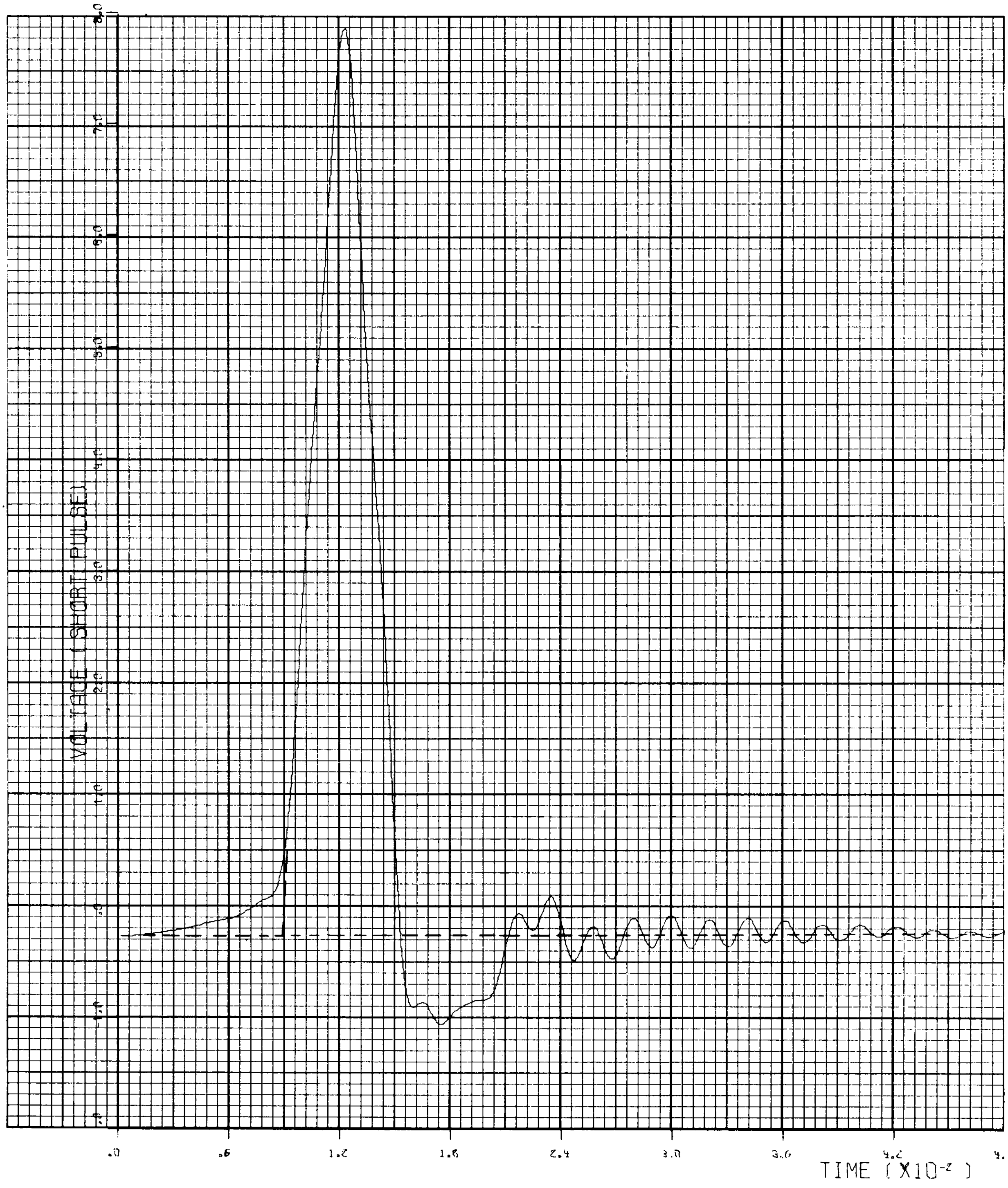


Fig. 5

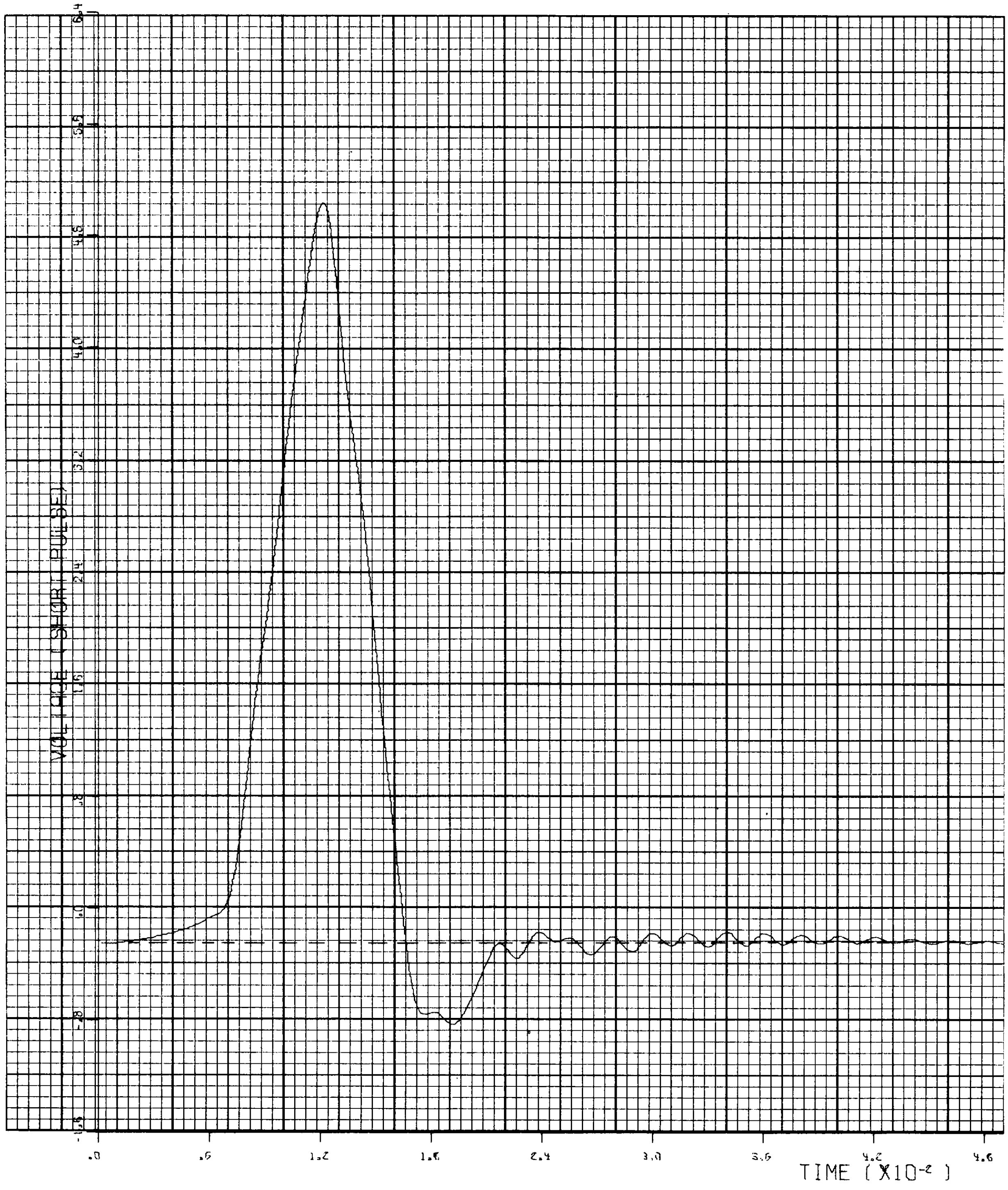


Fig. 6

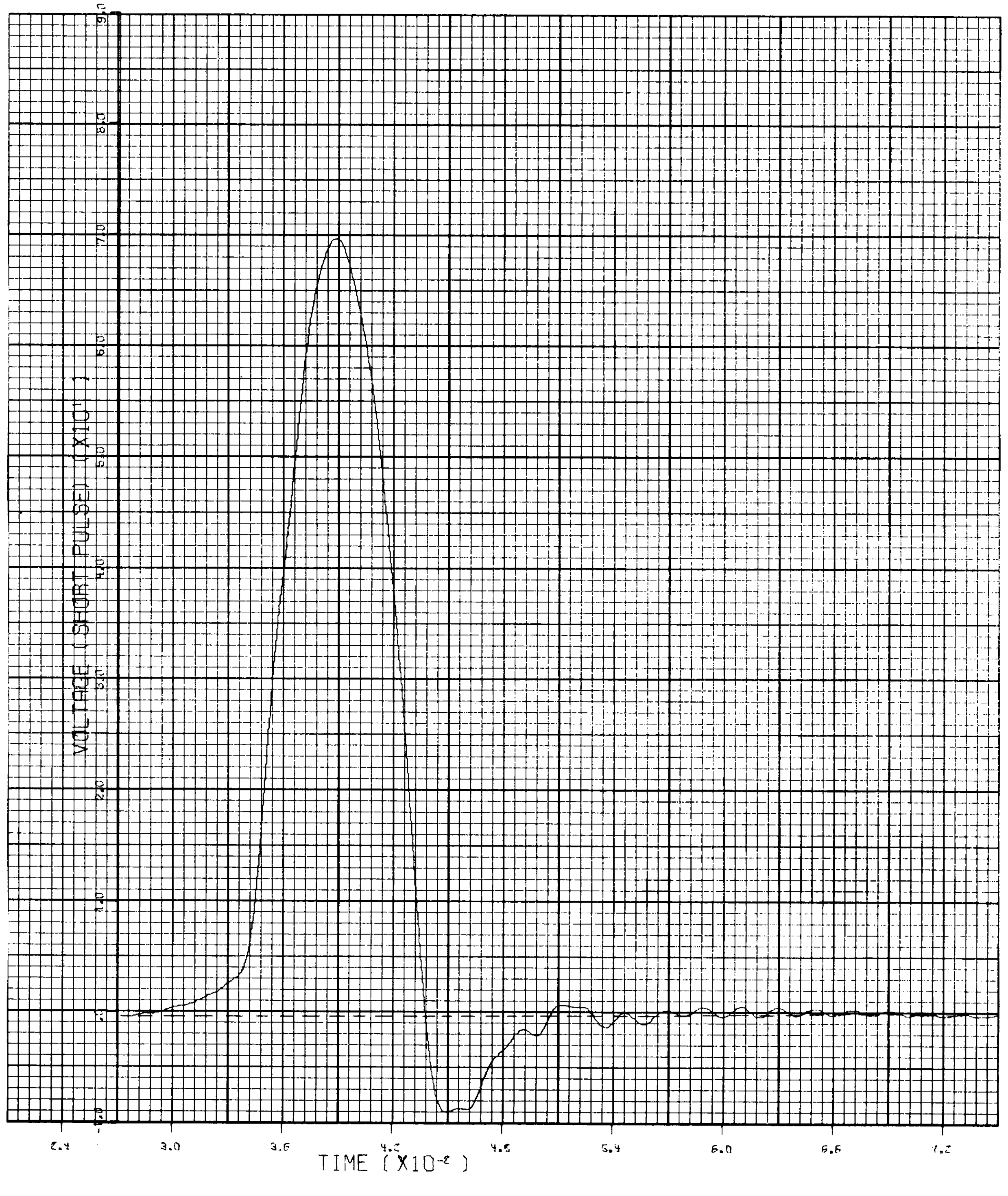


Fig. 7

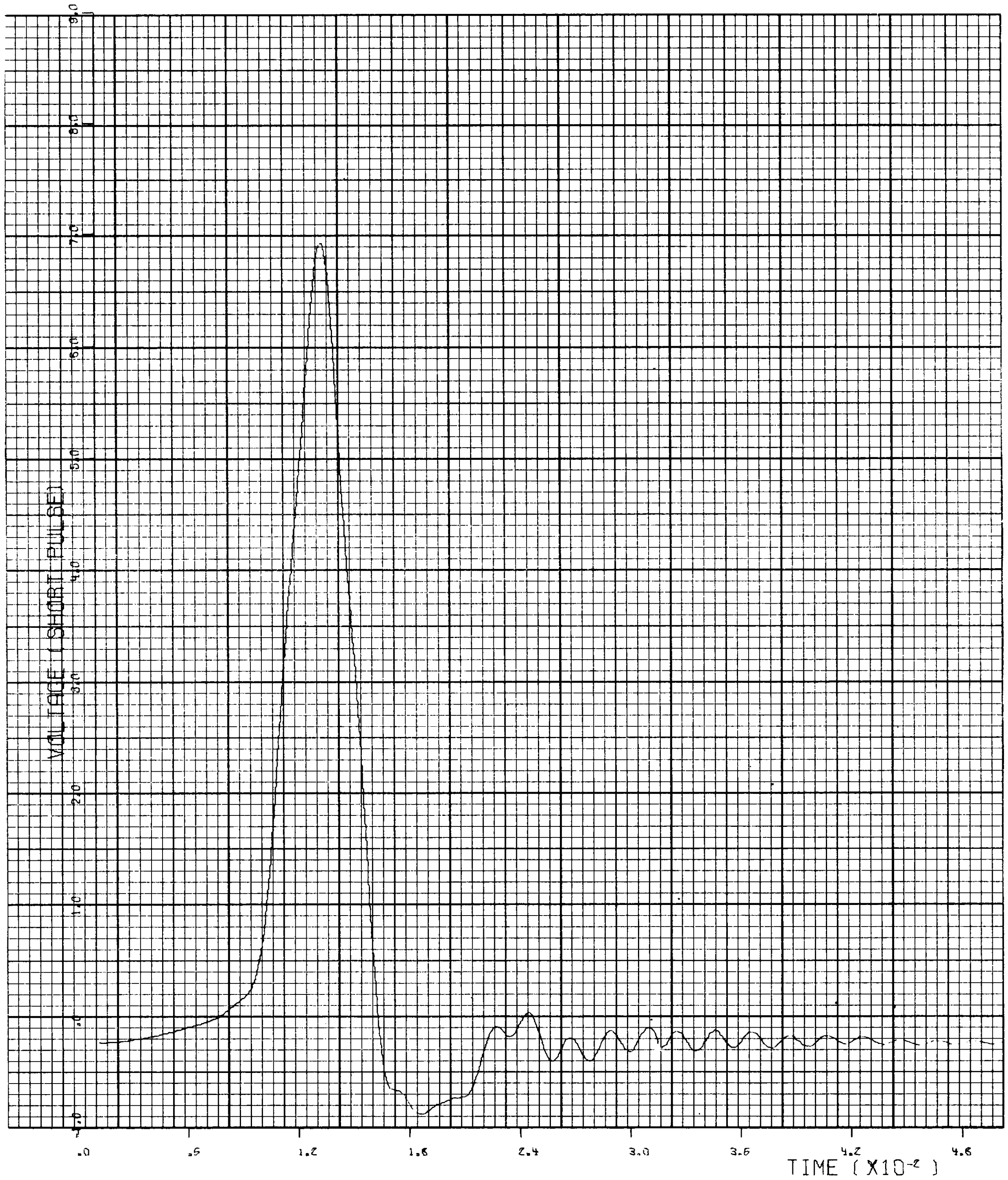


Fig. 8

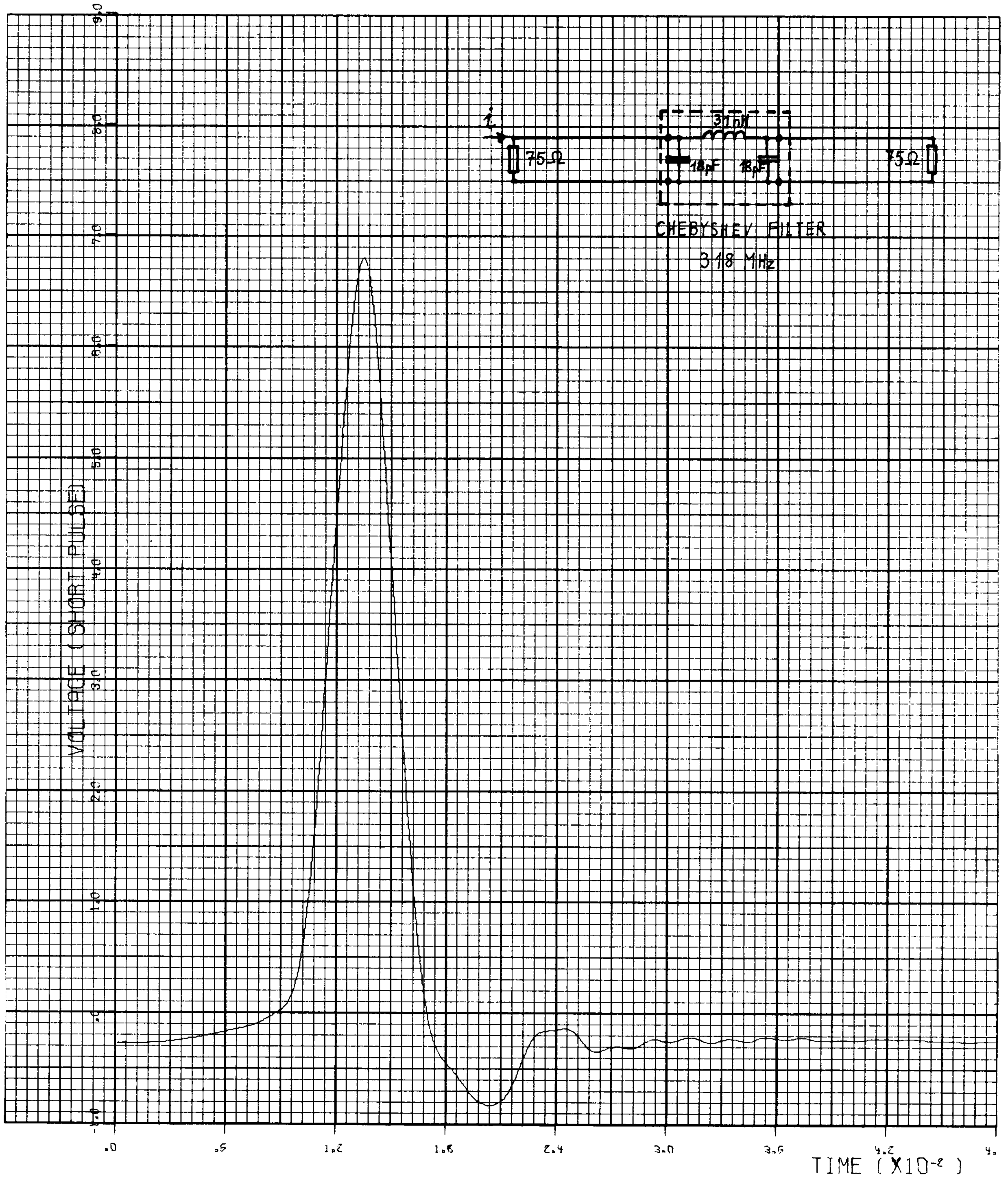

75Ω
31 nH
18pF
18pF
75Ω
CHEBYSHEV FILTER
318 MHz
VOLTAGE (SHORT PULSE)
TIME (X10⁻²)

Fig. 9

Floating base line at transition

(50 msec/cm)

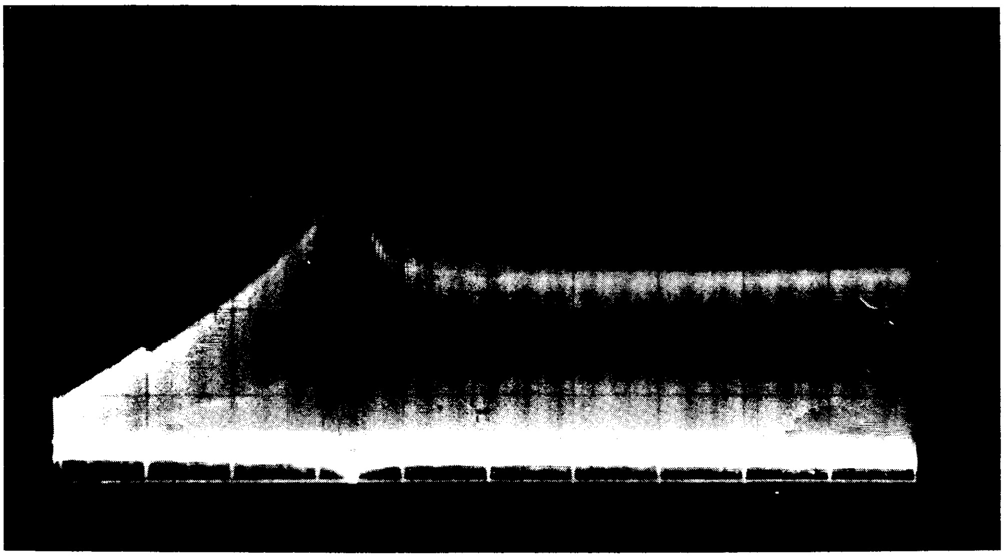


Fig. 10a

$0.95 \cdot 10^{12}$ protons/p

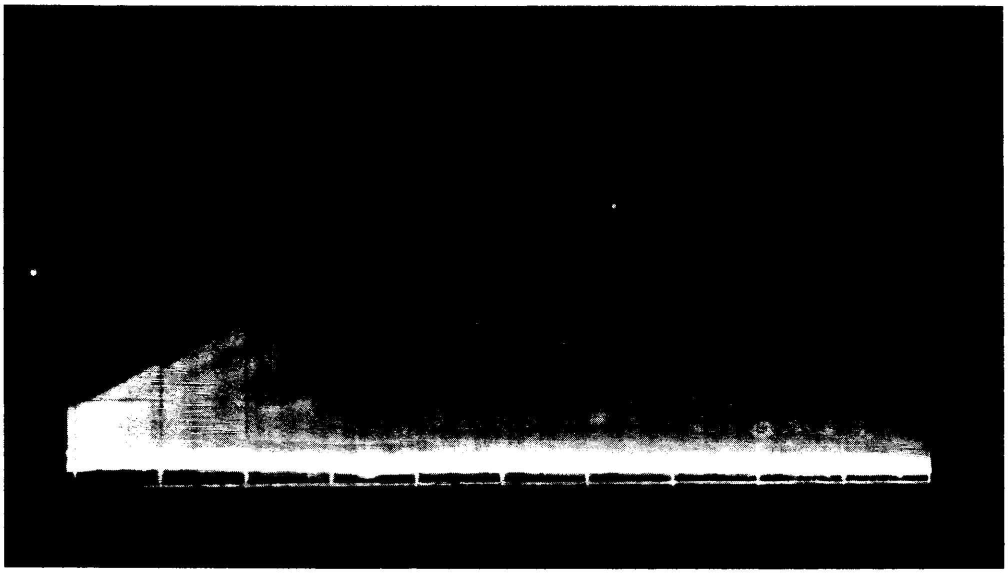


Fig. 10b

$0.30 \cdot 10^{12}$ protons/p

Center = 75 Ω

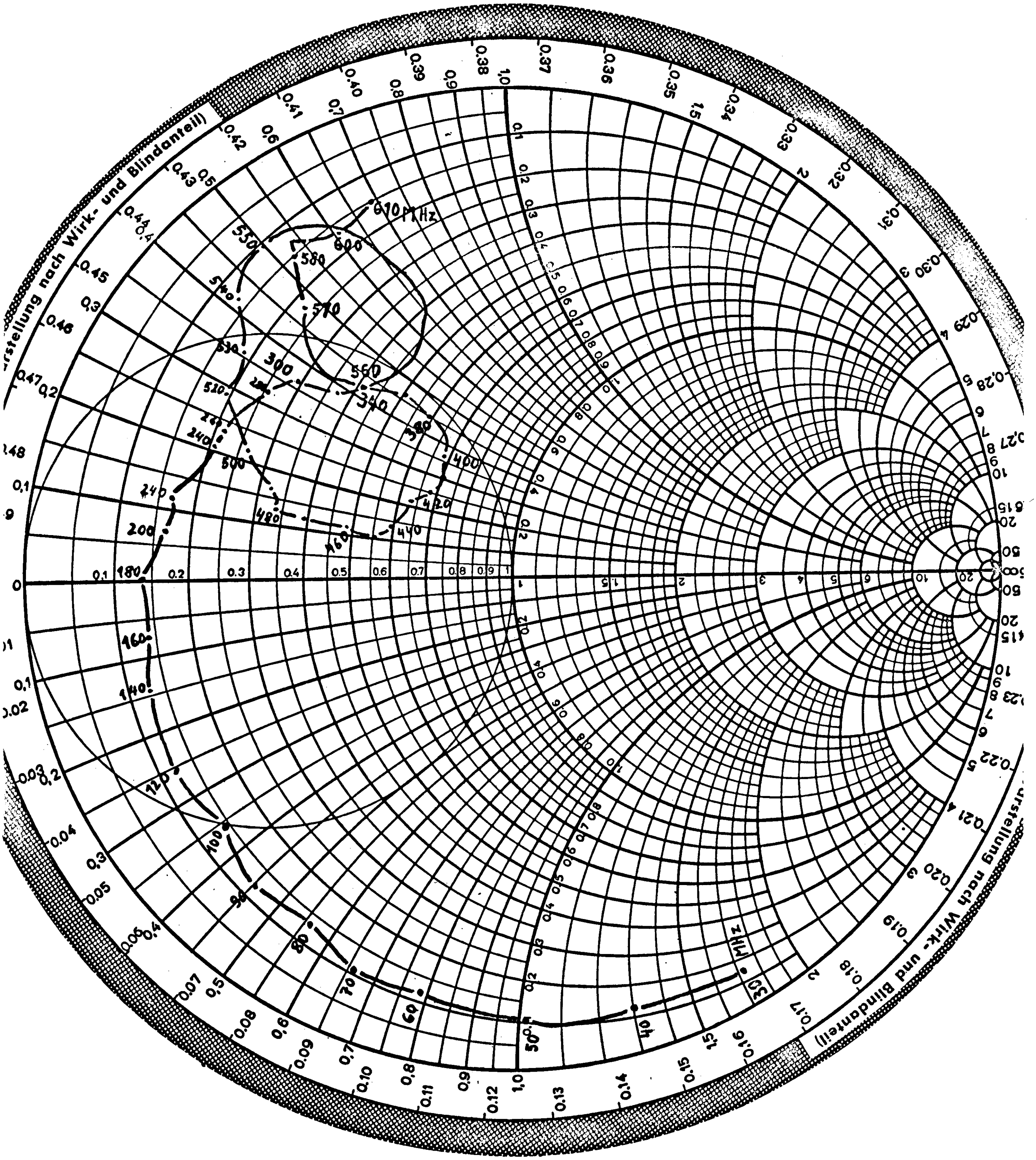


Fig. 11

Center = 75 Ω

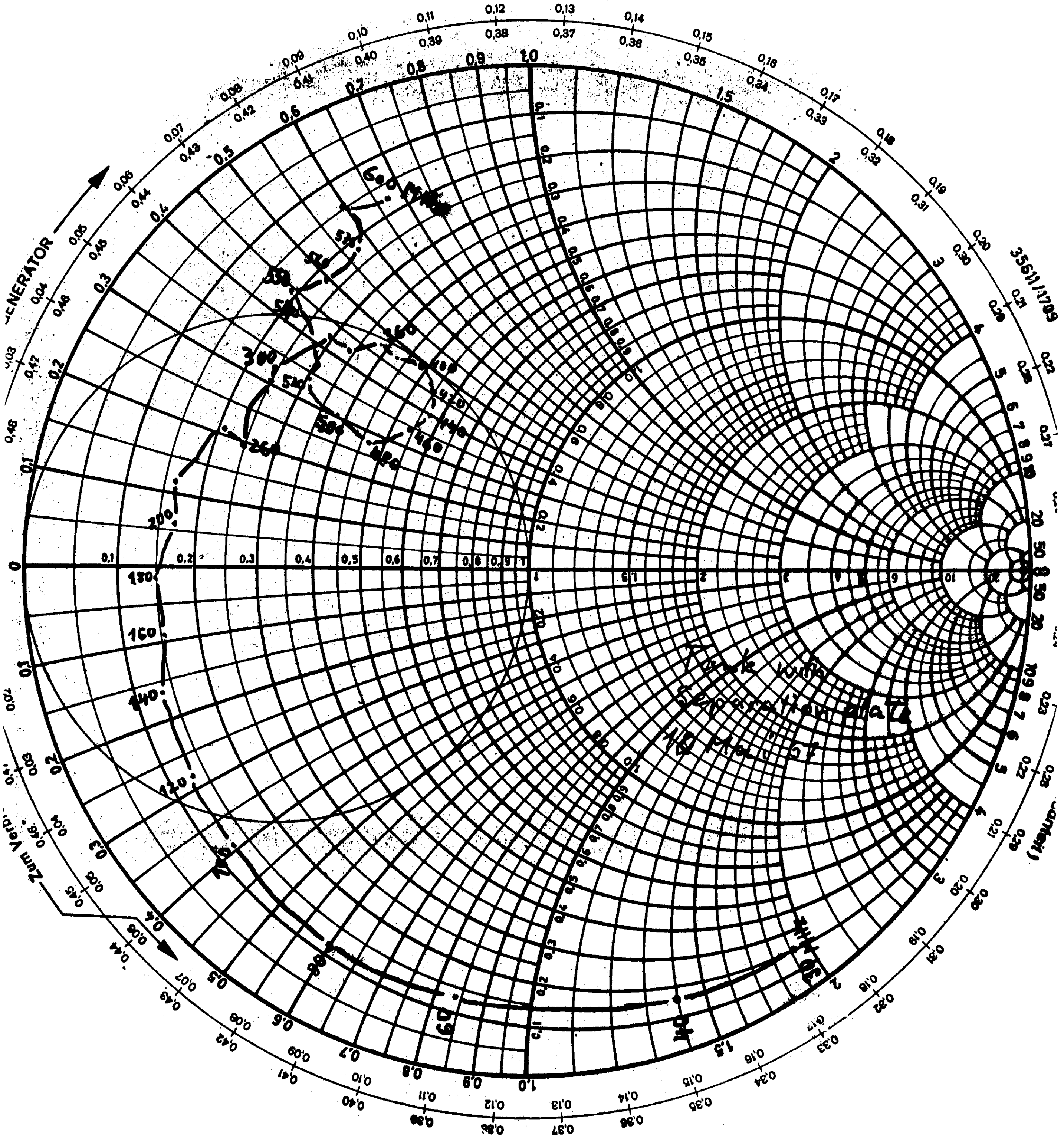


Fig. 12

Impedance of P.U. electrode in tank