# SOME SUGGESTIONS FOR IMPROVED POSITION P.U. ELECTRODES

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## 1. GENERAL CONSIDERATIONS

### 1.1 Linearity of P.U. electrodes (fig. 1)

A circulating proton beam induces opposite charges on the beam tube. When a section of this tube is replaced by an electrode, the charge on this electrode exactly compensates the beam charge present in its section.

Now, suppose an electrode of arbitrary cross-section but cylindrical in the direction of the beam movement. The horizontal projection of this electrode is a rectangle. We cut this electrode linearly, that is: the horizontal projection of the cut is a diagonal of the rectangle

It is clear that, for a beam moving infinitely near the boundary of the electrode, the charge induced on each half electrode is proportional to the horizontal deviation of the beam. It can be proved (ref. 1) that this is also true for each interior point. Moreover, small irregularities at the border are smoothed out at the interior points.

The charge induced on the two halves is:

$$q_A = - qo \frac{W/2 + x}{W} \qquad q_B = - qo \frac{W/2 - x}{W}$$

where : $q_A$, $q_B$ : charges induced on the electrode
$qo$ : charge of beam inside the electrode
$x$ : deviation of the beam from the center
$W$ : width of the electrode.

Any cross section is possible but, for practical reasons, usually a circular or a rectangular cross-section is used.

### 1.2 Calculation of the edge-effects:

Ideally, the electrode replaces a section of the beam tube but often this is not possible and the electrode must be placed in an enlarged vacuum tank. This introduces edge effects against which the electrode must be protected by guard rings. More charge is induced on the electrode than in the ideal case: the electrode appears longer than it really is. This effect is maximum for the beam centered and small for the beam near the border of the electrode.Up to now, to my knowledge, no published attempt was made to calculate this effect. In appendix A a calculation is made for a centered beam and an electrode with circular cross-section (radius $R_1$), placed in an infinitely extending vacuum chamber (radius $R_2$). Fig. 10 gives the apparent elongation of the electrode in function of the widt of the guard ring, a, and this for different values of $R_2/R_1$.

1.3 Electrical configuration of the electrode (fig. 2)

The electrode has capacity $C_A$ and $C_B$ to ground and mutual capacity $C_{AB}$. The electrode discharges into terminated coaxial cables with characteristic impedance $R_o$.

Suppose the beam modulated with frequency W. On the coaxial cables we find signals with amplitude $V_A$ and $V_B$. The ratio $V_A/V_B$ determines the position of the beam. This ratio is frequency independent (and,consequently, independent of the bunch shape) only if we put a resistor $R_{AB}$ in parallel with $C_{AB}$ and if:

$$R_{AB} = \frac{R_o\ C_A}{C_{AB}}$$

The position is then determined by;

$$x = \frac{W_a}{2} \quad \frac{V_A - V_B}{V_A + V_B}$$

and this for any bunch shape. In this formula, $W_a$ is the apparent width of the electrode. The relation with the fysical widt, $W_f$ is:

$$W_a = W_f \ \frac{C_A + 2\ C_{AB}}{C_A}$$

The effect of $CA_B$ is thus to reduce the sensitivity of the electrode.

1.4 Signals induced on the electrode

We suppose the beam centered. We further suppose the bunch-shape triangular with base-widt b and with N protons per bunch. With $\tau = R_o C_A$ small compared with the base-widt, we obtain the waveform of fig. 3 on the coaxial cables. The value of $V_A$ is given by:

$$V_A = V_B = 1,07 . 10^{-27} \frac{R_o . N . L}{b^2}$$

where L is the length of the electrode.

Example: with b = 20 n sec.

$R_o = 75$

$N = 5.10^{10}$ protons

$L = 12$ cm

we find : $V_A = 1,2$ Volt.

1.5 Calibration of the electrodes

Several constructors of P.U. electrodes have tried to calibrate their electrodes with a charged rod or wire simulating the beam. These calibrations are inaccurate for several reasons:

- the charge is unevenly distributed over the wire;
- edge effects are different from those of the electrode placed in its tank;
- difficulties with earth loops and standing waves
- R.F. measurement inaccuraties.

The net result is that the calibration is probably worse than the inherent geometrical accuracy of the electrode.

At the Argonne National Laboratory, a system was constructed to calibrate the electrodes with a relativistic electron beam (ref. 2). The method is too involved to be copied here but an important result of these measurements was that the electrodes were found to behave as calculated, within the mechanical and electrical tolerances.

## 2. THE P.U. STATIONS FOR FES

We propose to construct two different models, a large one for monitoring the internal beam and a small one for monitoring the external beam.

2.1 The large P.U. electrodes

The following large P.U. electrodes planned:

P.U.1 : in S.S. 16, centered on $r = 0$

P.U.2 : in S.S. 24, centered on $r = 0$

P.U.3 : in S.S. 26, centered on $r = -25$ mm

P.U.4 : in S.S. 28, centered on $r = 0$

For all these electrodes we take:

widt : $W_f$ = 21 cm

height : H = 11,5 cm

length : L = 12 cm (+ 2 guard rings)

With these dimensions and positions, the beam at injection is not hindered and all trajectories pass through the 4 P.U. stations, except trajectory $\omega$, which does not pass through P.U.4.

### 2.2 The guard rings for the large P.U. electrodes

The end-effect on the electrodes is studied in appendix A. This study was made for electrodes with circular dross-section but it is usefull for rectangular electrodes as well if a suitable value for an "equivalent" $R_1$ can be found. For the large electrodes, $R_1$ is estimated to be 8 cm. The electrodes are placed in a vacuum tank about 2,5 times wider and higher than the electrode. Consequently, we take $R_2/R_1$ = 2,5.

The electrodes are mounted approximately in line with the beam tube and with one extremity (say, the B electrode) close to one end of the vacuum tank. Consequently, the end effect is mainly on electrode A. Instead of a signal $V_A$, we will have a signal $V_A + \Delta V_A$ with:

$$\frac{\Delta V_A}{V_A} = \frac{2\,\Delta l}{L}$$

and a position reading:

$$x + \Delta x = \frac{W_a}{2} \; \frac{V_A + \Delta V_A - V_B}{V_A + \Delta V_A + V_B}$$

For a centered beam, where the effect is maximum, this becomes ($V_A = V_B$) :

$$x = \frac{W_a}{4} \cdot \frac{\Delta V_A}{V_A} = \frac{W_a}{2} \cdot \frac{\Delta l}{L}$$

if x = 0,5 mm is tolerated, then: (for $W_a = W_f$ = 21 cm)

($\Delta$l) max = 0,5 mm

this corresponds to a guard ring:

a $\cong$ 10 cm

In this case it seems better to continue the guard ring at both ends until it joins the beam tube. This will also prevent standing waves from building up in the vacuumtank.

### 2.3 The small P.U. electrodes:

All these stations are centered on the ejected beam.

P.U.5 : in S.S.28

P.U.6 : somewhere on the ejected beam
P.U.7 : before the target (hor. pos.)
P.U.8 : before the target (vert. pos.)
P.U.9 : in S.S. 30 (channel B)

} these electrodes are not planned but can be installed if necessary.

For all these electrodes we take:

widt : Wf = 7 cm

height : H = 7 cm

lenght : L = 12 cm (+2 guard-rings)

### 2.4 The guard-rings for the small P.U. electrodes

The small P.U. electrodes must be able to operate on the external beam, even when it is not surrounded by a conducting vacuum chamber. In this case $R_2$ is the distance to the nearest conducting objects and $R_1$ is about 4 cm. We take $R_2/R_1 = 50$ and, for $(\Delta x)$ max = 0,5 mm

$$a \cong 4 \text{ cm}$$

## 3. CONSTRUCTION OF THE P.U. ELECTRODES

### 3.1 The actual P.U. electrodes

The actual electrodes, installed in a vacuum tank in S.S.37 have a rectangular cross-section. They are made of plied messing, insulated with commercial ceramic spacers. For details see drawing 303 - 129 - 0. Errors of more than 1 mm are probable due to mechanical tolerances and also due to edge effects. The electrical characteristics are:

$$C_A = C_B = 52 \text{ pF}$$

$$C_{AB} = 15,5 \text{ pF}$$

Another type of electrode with better mechanical tolerances and smaller $C_{AB}$ is desirable.

## 3.2 The new electrodes (fig. 4, 5, 6)

The new electrodes consist of two glass (or ceramic) plates for the horizontal part and machined messing spacers for the vertical parts. The glass plates are covered with conducting paint and the electrode shape is etched out by photolitographic means. A grounded strip between the two half electrodes reduces $C_{AB}$ to a negligible value. Contact between silver paint and messing spacers is made by means of gold or indium wires pressed between them. The whole structure is surrounded by a screen to equalise the ground capacity.

## 3.3 Mounting of the electrodes in the vacuum tank

The electrodes are mounted between grounded guard electrodes, which make a more or less continous junction with the beam tube. Contact with the electrode screen is made by means of berillium-copper springs. In order not to damage these springs when inserting the P.U., a solid guiding mechanism has to be provided. For details see fig. 7.

The right guard electrode is about 12 cm long. A luminescent screen or, eventually, a beam profile monitor can be mounted inside it.

## 3.4 Electrical connections to the electrodes

The electrodes are connected to analog - to - digital converters in the local control room. The connection is made by means of long coaxial cables. $C_2$, $L_2$ and $L_3$ prevent circulation currents from flowing between the earth connections of the P.S. and of the local control room. This set-up was tried on the actual electrodes, mounted in the C.P.S., and the resulting S/N ratio was better than 40 db.

By means of $S_1$, a thermal mercury switch, the two electrodes can be shorted together. The signal on both electrodes is then exactly equal and this allows to equalise the two transmission channels, including the A.D.C.. This relay is actuated via $L_4$, $L_1$ and the signal cables. $R_1$ prevents static charge to accumulate on the electrodes.

## Appendix: EDGE EFFECT OF P.U. ELECTRODES

### 1. Indroduction

Ideally, the electrodes replace a section of the beam chamber, but often this is not possible and the electrodes must be placed in an enlarged vacuum tank. This indroduces edge effects against which the electrodes must be protected by guard rings. This effect is maximum for the beam near the center and zero for the beam near the boundary of the electrodes. Here we calculate the necessary widt of the guard rings.

### 2. Reduction of the problem

Fig. 9 a gives the general configuration. At left the electrode with guard ring. We suppose the electrode extends infinitely to the left. The electrode is placed in a larger cylindrical chamber, also supposed to extend infinitely. We must calculate the field inside the electrode or, more precisely, the difference of this field with this of the ideal configuration (guard ring infinitely extending to the right) of fig. 9 b. This difference field can be obtained by substracting the boundary conditions of fig. 9 b from those of fig. 9 a. This gives the configuration of fig. 9 c.

This last configuration can be solved analytically. Our first concern is now to find an approximate value for $V_1$ (z).

### 3. Determination of $V_1$ (z)

Consider the vacuum tank without electrode (fig. 9 d). We substract the boundary conditions of fig. 9 a from those of fig. 9 d and we get the configuration of fig. 9 e. This configuration was realised in a tilted electrolytical trough and $V_1(z)$ was plotted for a wide range of $R_2/R_1$. The following empirical relation gives a good fit for the obtained curves:

$$V_1 (z) = \frac{k}{2\pi \epsilon_0} \ln \frac{R_2}{R_1} \left[ 0,18 + 0,82 \left(1 - e^{-\frac{1}{\tau} \frac{z}{R_1}}\right) \right]$$

with

| $R_2/R_1$ | $\tau$ |
|---|---|
| 1,25 | 0,31 |
| 1,5 | 0,48 |
| 2 | 0,74 |
| 3 | 1,70 |
| 4 | 2,10 |
| 8 (and up) | 3,50 |

4. Edge effect

With $V_1$ (z) known, we calculate the field inside the electrode. This field was calculated (ref. 3) for the case $V_1$ (z) = $V_c$ (constant pot.):

$$V_4(\rho,z) = V_c\left[1 - \sum_{\alpha=1}^{\infty} \frac{J_0(m_\alpha \rho)}{(m_\alpha R_1).J_1(m_\alpha R_1)}\, e^{-m_\alpha z}\right]$$

where $J_0$ and $J_1$ are the Bessel functions of order 0 and 1; $m_\alpha R_1$ are the positive roots of $J_0(m_\alpha R_1) = 0$: $m_1R_1 = 2{,}40$

$m_2R_1 = 5{,}52$

$m_3R_1 = 8{,}65$ etc.

We are interested in the charge induced by this field on the electrode at x = -z (fig. 9 a):

$$q_i(x) = -2\pi R_1 \epsilon_0 E_\rho(R_1,x) = 2\pi R_1 \epsilon_0 \left[\frac{\partial V_4(\rho,x)}{\partial \rho}\right]^{\rho=R_1} . V_c$$

$$= -2\pi\epsilon_0 V_c \sum_{\alpha=1}^{\infty} e^{-m_\alpha x}$$

for a changing voltage $V_1(z)$, this charge is:

$$q_i'(x) = -2\pi\epsilon_0 \int_0^\infty \frac{dV_1(z)}{dz} \sum_{\alpha=1}^{\infty} e^{-m_\alpha(x+z)}\, dz$$

$$= -k \ln\frac{R_2}{R_1} \sum_{\alpha=1}^{\infty} e^{-m_\alpha x}\left(0{,}18 + \frac{0{,}82}{1+\tau . m_\alpha R_1}\right)$$

The total edge-charge on the electrode is then:

$$\Delta Q = \int_a^\infty q_i'(x)\,dx = -k \ln\frac{R_2}{R_1} \sum_{\alpha=1}^{\infty}\left(0{,}18 + \frac{0{,}82}{1+\tau . m_\alpha R_1}\right)\frac{e^{-m_\alpha a}}{m_\alpha}$$

and the apparent elongation of the electrode is:

$$\boxed{\frac{\Delta l}{R_1} = \frac{-\Delta Q}{R_1 . k} = \ln\frac{R_2}{R_1}\sum_{\alpha=1}^{\infty}\left(0{,}18 + \frac{0{,}82}{1+\tau . m_\alpha R_1}\right)\frac{e^{-m_\alpha R_1 \cdot \frac{a}{R_1}}}{m_\alpha R_1}}$$

This function is plotted on fig. 10.

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References:

1) A.I. Sherwood. Electrostatic induction electrode systems for beam-position detection. IEEE Trans. on Nucl. Sci, June 1965, p. 925-28.

2) I.R. Simanton. Calibrating induction electrodes using cathode ray beams. IEEE Trans. on Nucl. Sci., June 1969, p. 932-33.

3) E. Weber. Electromagnetic Fields. Vol. 1 - Mapping of Fields, p. 430. John Wiley and Sons,Inc., New York.

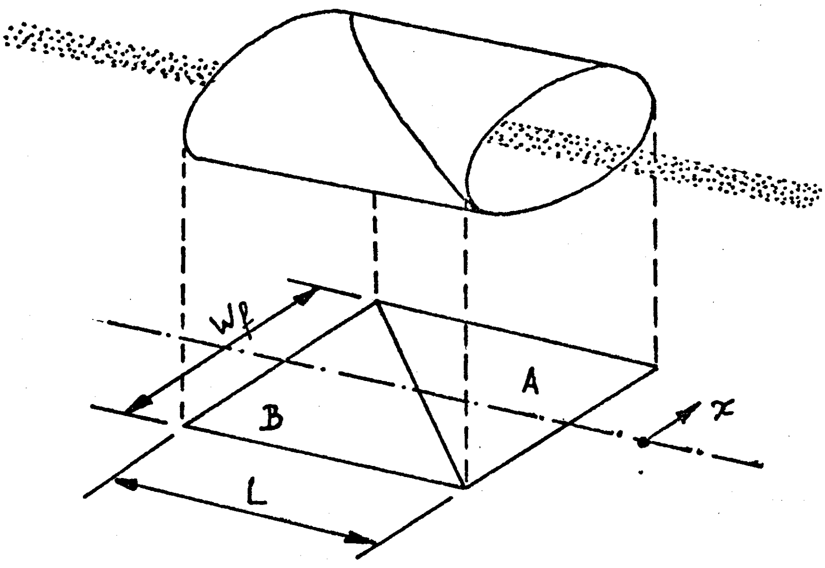



fig. 1: the electrostatic induction electrode.

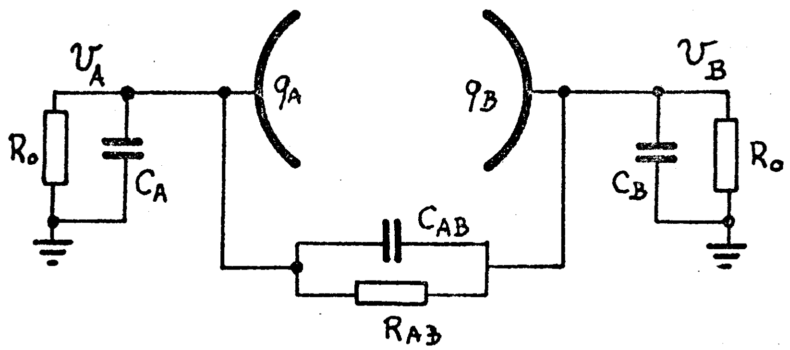



fig. 2: electrical configuration of the electrode.

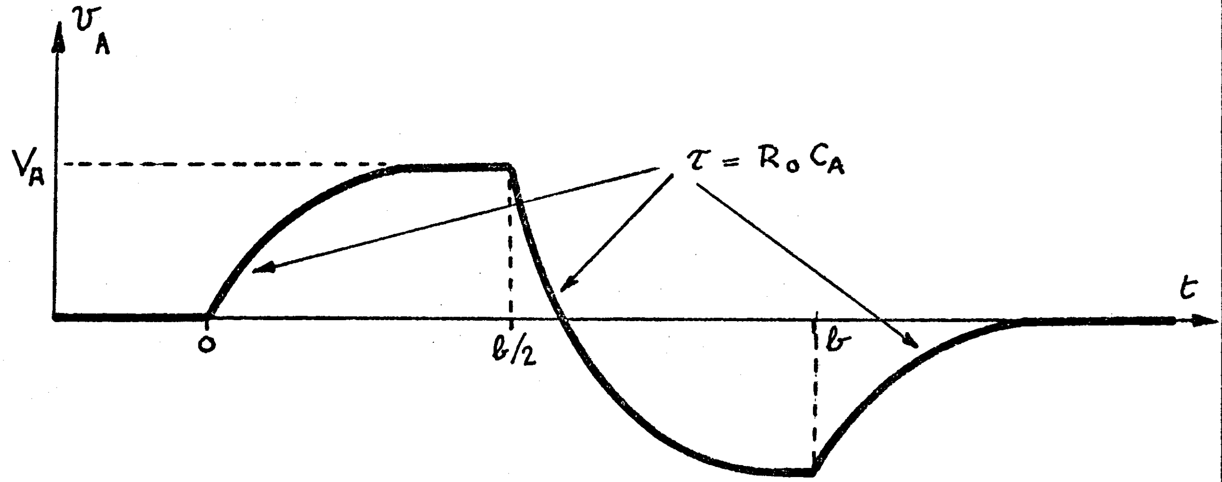



fig. 3: waveform $v_A(t)$ for a triangular bunch with widt b.

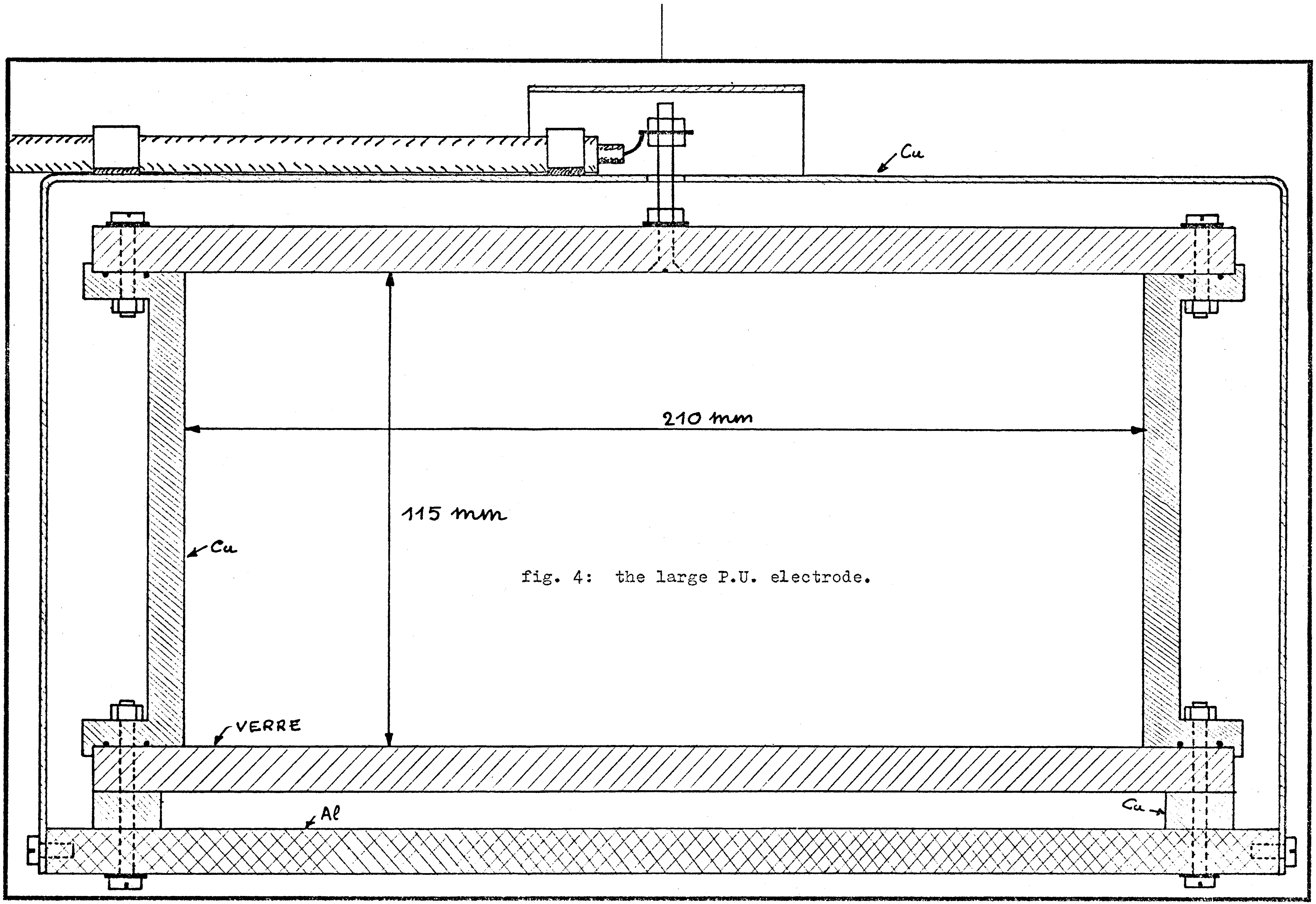
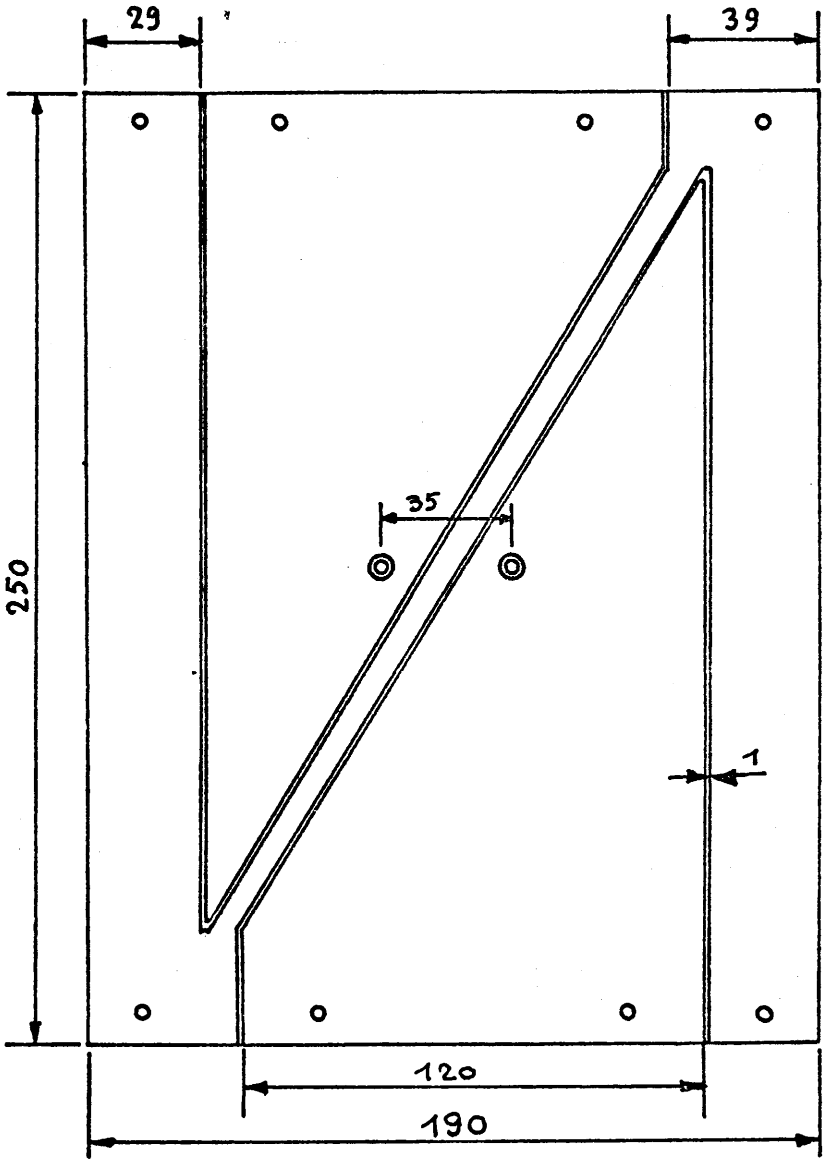
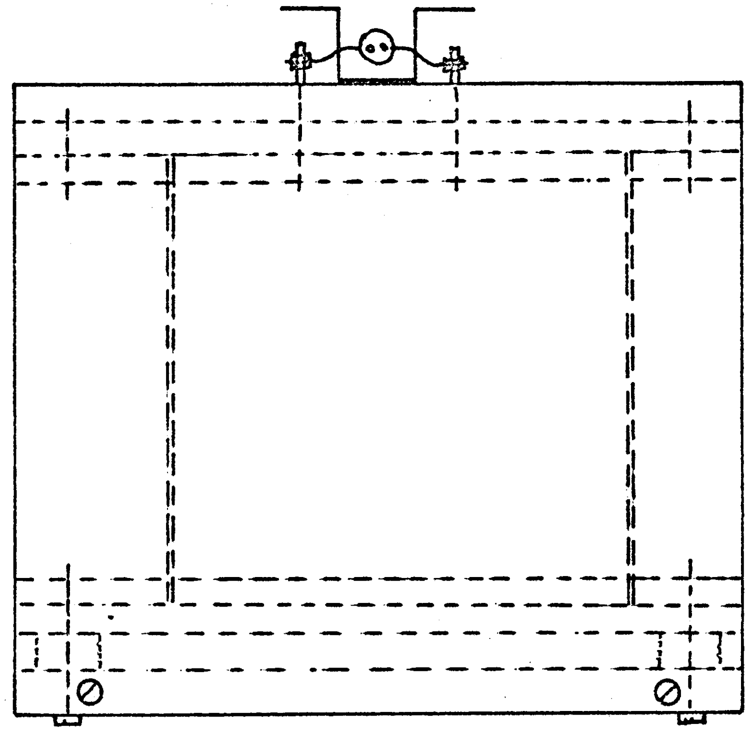



fig. 4: the large P.U. electrode.




A



B

fig. 5: the large P.U. electrode
A - upper (or lower) glass plate
B - side view

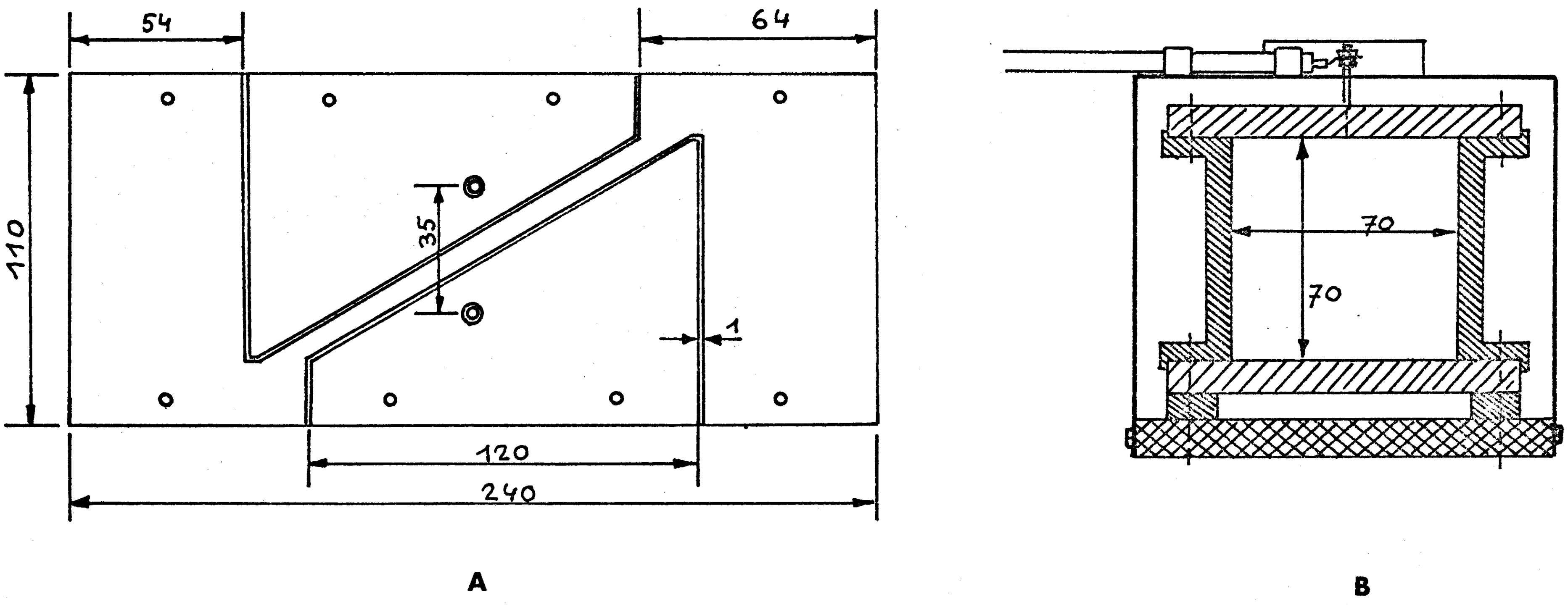



fig. 6: the small P.U. electrode
A - upper (or lower) glass electrode
B - longitudinal view

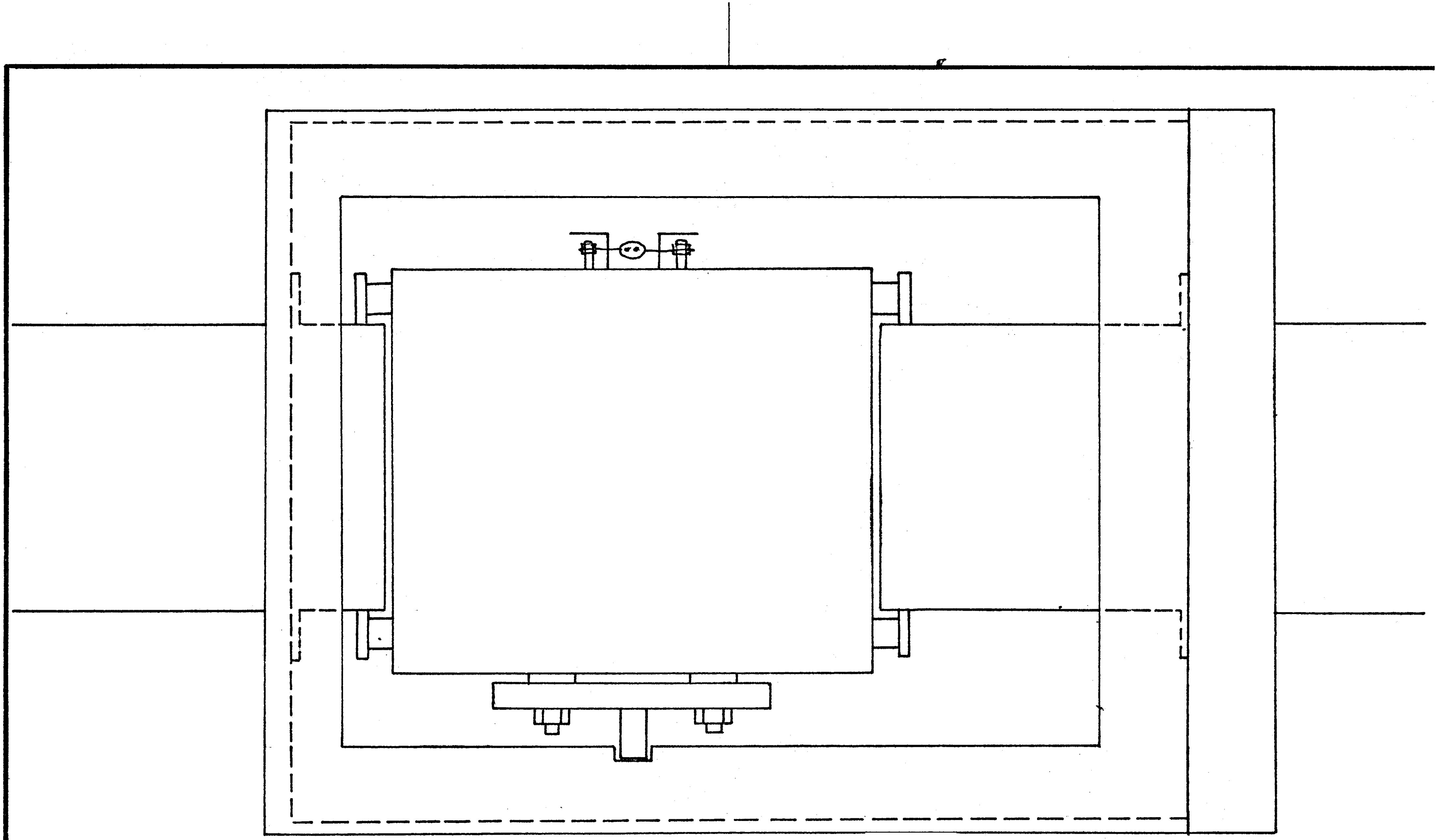
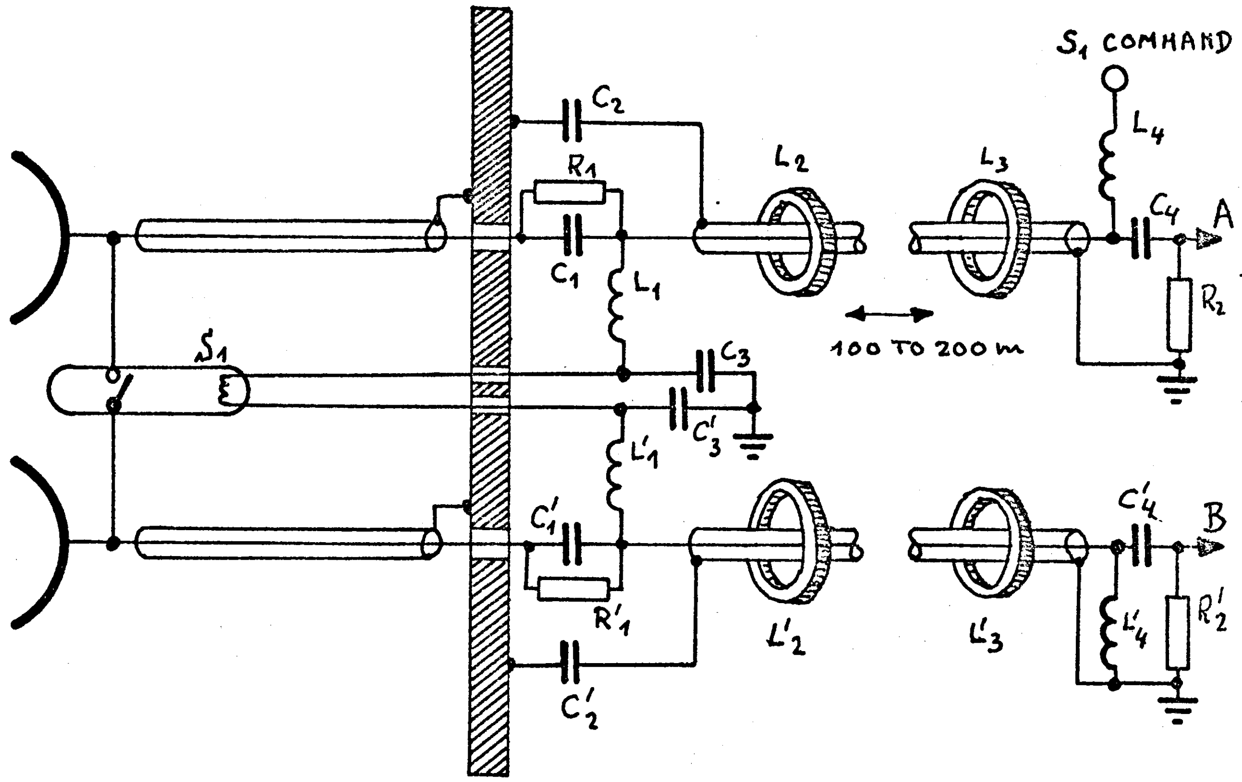


fig. 7: the large P.U. electrode mounted in its vacuum tank




ALL CAPACITORS : 10 nF CERAMIC

$R_1 = R'_1$ : 470 Ω
$R_2 = R'_2$ : 75 Ω

$L_1 = L'_1 = L_4 = L'_4 = 330\,\mu H$
$L_2 = L'_2 = L_3 = L'_3 \cong 0{,}3\,\mu H$

fig. 8: electrical connections to the P.U. electrode.

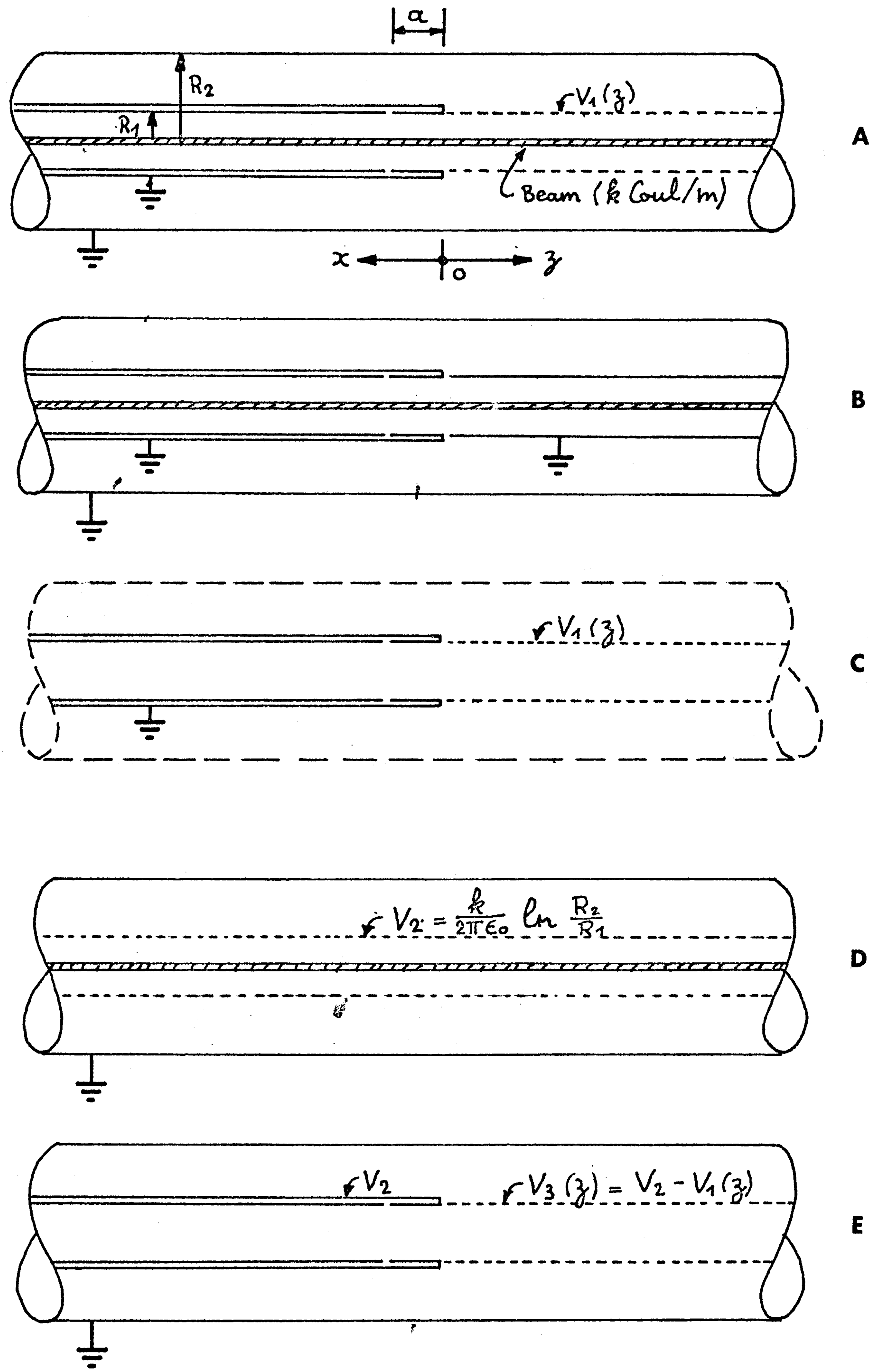

a
R2
R1
V1(z)
Beam (k Coul/m)
x
o
z
A
B
V1(z)
C
V2 = k/(2πε0) ln R2/R1
D
V2
V3(z) = V2 - V1(z)
E

fig. 9

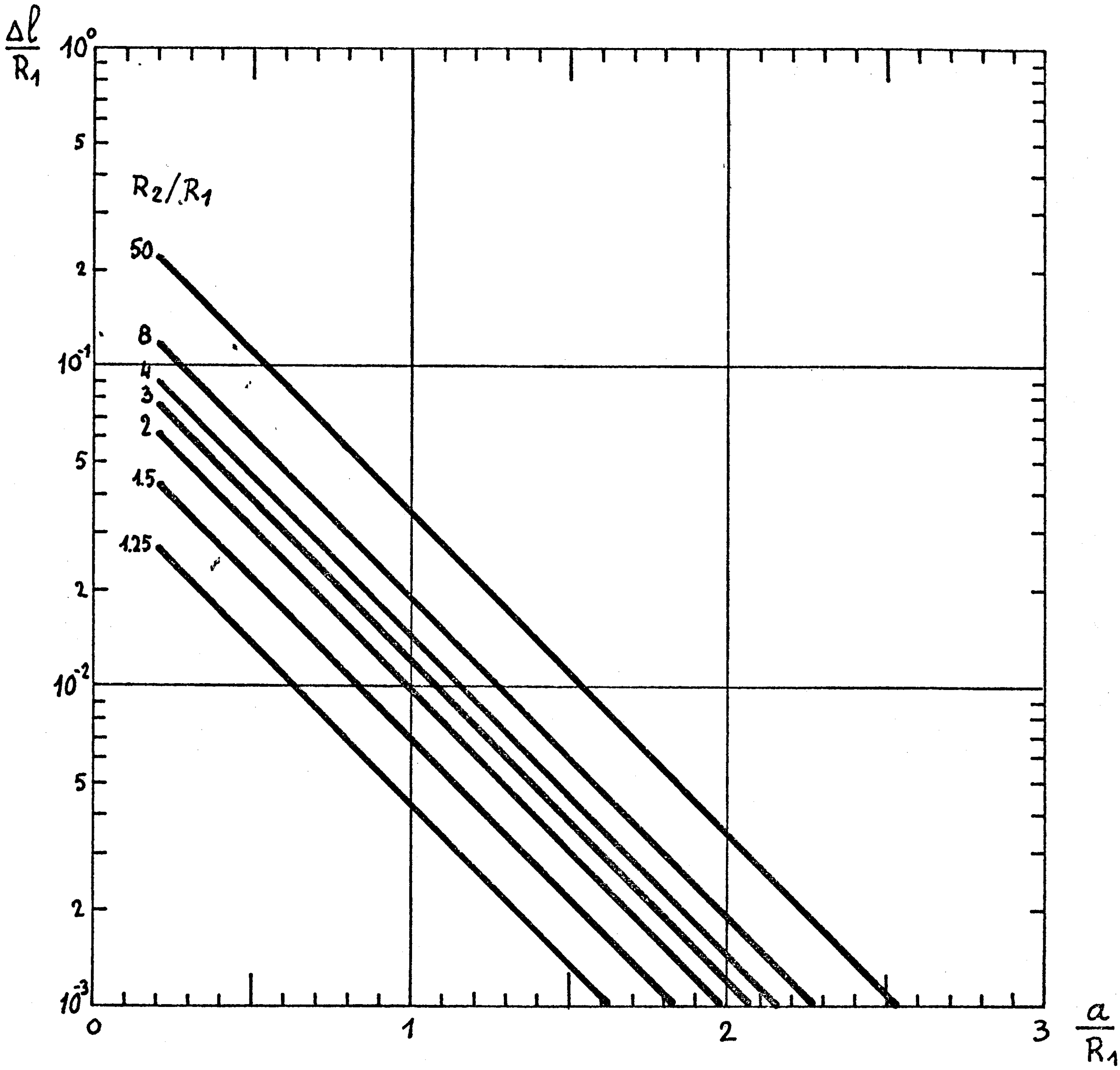



Fig. 10 : apparent elongation of the electrodes in function of the width of the guard ring.