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PROPOSAL FOR A RESISTIVE, NON-DESTRUCTIVE UHF WIDE-BAND PICK-UP STATION WITH BEAM POSITION MEASUREMENT

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Table of Contents

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Summary

This paper proposes a resistive PU station which would allow measuring the longitudinal high frequency structure of a bunched proton beam with a bandwidth of 2 GHz. Furthermore, it would detect the horizontal and vertical beam position with a resolution better than 0.1 mm. The required mechanical length in beam direction is 1 cm.

After the requirements, the considerations and calculations which led to the proposed solution are given.

A cost estimate is included.

1. Introduction

This proposal is based on the requirements of the planned new Linac for which the detector can possibly be used.

The following specifications were determined by P. Têtu, at a meeting on 30 May, 1973.

2. Requirements

- Mechanical longitudinal length		< 2 cm
- diameter of the vacuum chamber		5 cm
- cable length to the observation point		20 m
- energy of the beam at the measuring point		∿ 750 keV
- bunch frequency		∿ 200 MHz
- bunch length		∿ 1 ns
- frequency bandwidth		2 GHz
- mean beam current	min	> 180 mA
- mean beam current	max	< 250 mA
- peak beam current		1.5 A

A special problem is the presence of secondary electrons due to beam losses and ionization. Furthermore, the 200 MHz acceleration voltage must not disturb the pick-up station which should be mounted very near to the input of the acceleration tank 1.

3. General Considerations

The selection of the pick-up type (electrostatic, magnetic or resistive) is mainly influenced by the sources of disturbances. Both the electrostatic and magnetic PU's are sensitive to stray fields of the acceleration tank.

A resistive PU station[1,2,3] which is sensitive to the image current of the beam seems much less sensitive to external stray fields if the resistive gap is short ($\approx$ 1 mm). It is also much less sensitive to secondary electrons if the gap and its resistance are small. The relatively high beam current allows small resistances. Furthermore, the mechanical length required for the resistive PU is much smaller than the length required for the other types. This is the reason why the resistive type of PU seems to be best suited for this purpose.

The low frequency limit can be determined by considering the base line of the signals. A horizontal base line can be obtained when the drop (or rise) during 5 ns remains small. A drop of 5% leads to a time constant

$$\tau = \frac{5 \text{ ns}}{5\%} = 100 \text{ ns}$$

and to a required lower frequency limit

$$f_L = \frac{1}{2\pi\tau} = \frac{10^9}{6.28 \cdot 100} = \underline{1.59 \text{ MHz}}$$

4. Characteristics of the Resistive PU-Station

4.1 Intensity Detection

If the conducting vacuum chamber is interrupted by a uniformly distributed resistive layer (or several lumped resistors) of about 1 mm length, the image current I_i on the chamber wall (which equals the beam current I_B for short pulses) generates a voltage U across the resistive gap (fig. 1).

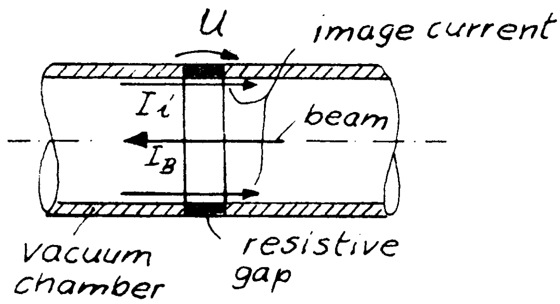


Fig. 1

The gap capacity determines (with the gap resistance) the high frequency limit f_H.

The low frequency limit f_L is given by the inductance of the external short-circuit of the two parts of the vacuum chamber. A ferrite core with an external short-circuit suitably defines this inductance (fig. 2).

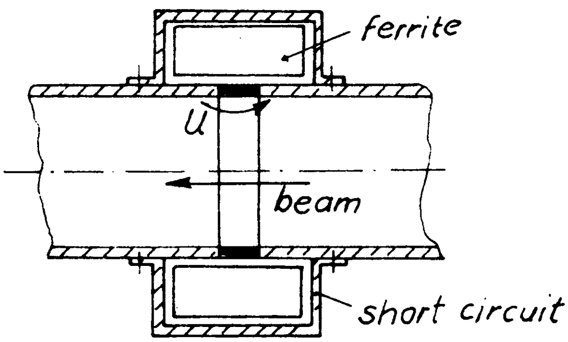


Fig. 2

The electrical equivalent circuit of such a resistive PU station is shown in fig. 3.

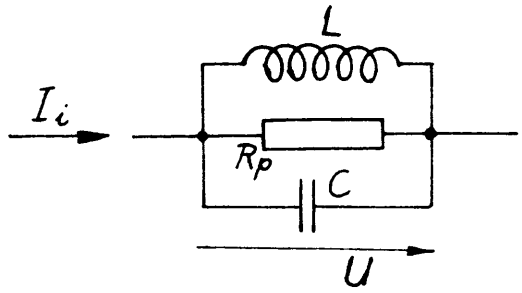


Fig. 3

The generated signal is (with $p = j\omega$)

$$U = I_i \underline{R} = I_i \frac{R_p}{1 + pCR_p + \frac{R_p}{pL}}$$

or

$$\frac{U}{I_i} = \frac{R_p}{1 + j\left(\frac{\omega}{\omega_H} - \frac{\omega_L}{\omega}\right)} \qquad (2)$$

with the high frequency limit

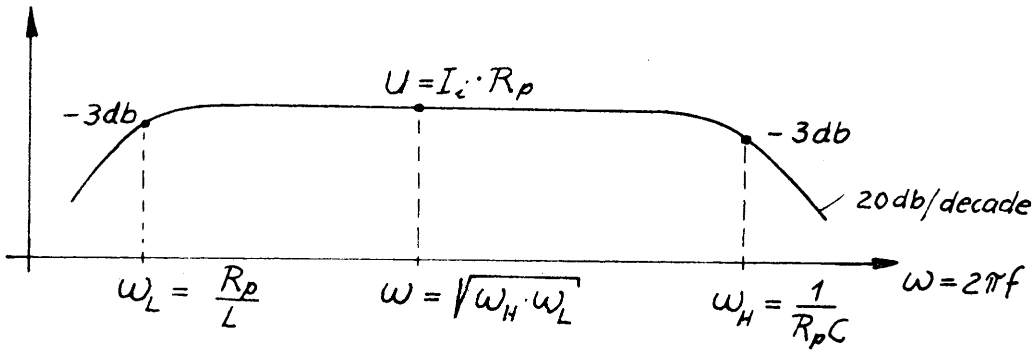
$$\omega_H = \frac{1}{R_p C} \qquad (3)$$

and the low frequency limit

$$\omega_L = \frac{R_p}{L} \qquad (4)$$

The frequency response is shown in fig. 4.

Fig. 4



The output signal is practically

$$U = I_i \cdot R_p \tag{5}$$

within the total transmission range

$$\omega_L < \omega < \omega_H$$

The bandwidth is inversely proportional to the resistance R_p.

4.2 Position Detection

The position detection is based on the non-uniform image charge distribution on the chamber wall (for an off-centre beam). The charge distribution was evaluated by conformal mapping (cf. equ.(15)) in ref.[4] and it appears later also in refs.[2,3] (simplified version).

$$q(r,\phi,\chi) = \frac{1 - r}{1 + r^2 - 2r \cos (\phi-\chi)} \tag{6}$$

The parameters are explained in Fig. 5.

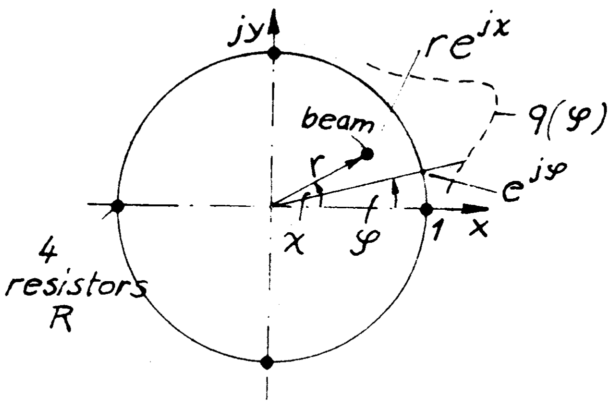


Fig. 5

The influenced charge versus angle ϕ is plotted in fig. 5a

With 4 resistors R as indicated in fig. 5, the charge has to cross the gap at 4 points and produces 4 voltages.

$$U_\nu = i_\nu \cdot R = R \frac{d}{dt} \int_{\phi=\frac{2\nu-1}{4}\pi}^{\frac{2\nu+1}{4}\pi} q(\phi)d\phi \tag{7}$$

with $\nu = 0, 1, 2, 3$

The voltage differences $\Delta U_H = U_0 - U_2$ (8)

and $\Delta U_V = U_1 - U_3$

can be used for beam position detection.

Equations (8), (7) and (6) were solved with a computer program for a beam moving in 10 steps from x = 0 to x = 1 with y as parameter (y = 0; 0,2; 0,4; 0,6; 0,8).

The result is shown in fig. 6. The function of the difference voltage is linear for small beam displacements, the linearity error for $|y| \leq 0,3$ and $|x| \leq 0,3$ being less than 3% (cp. fig. 6).

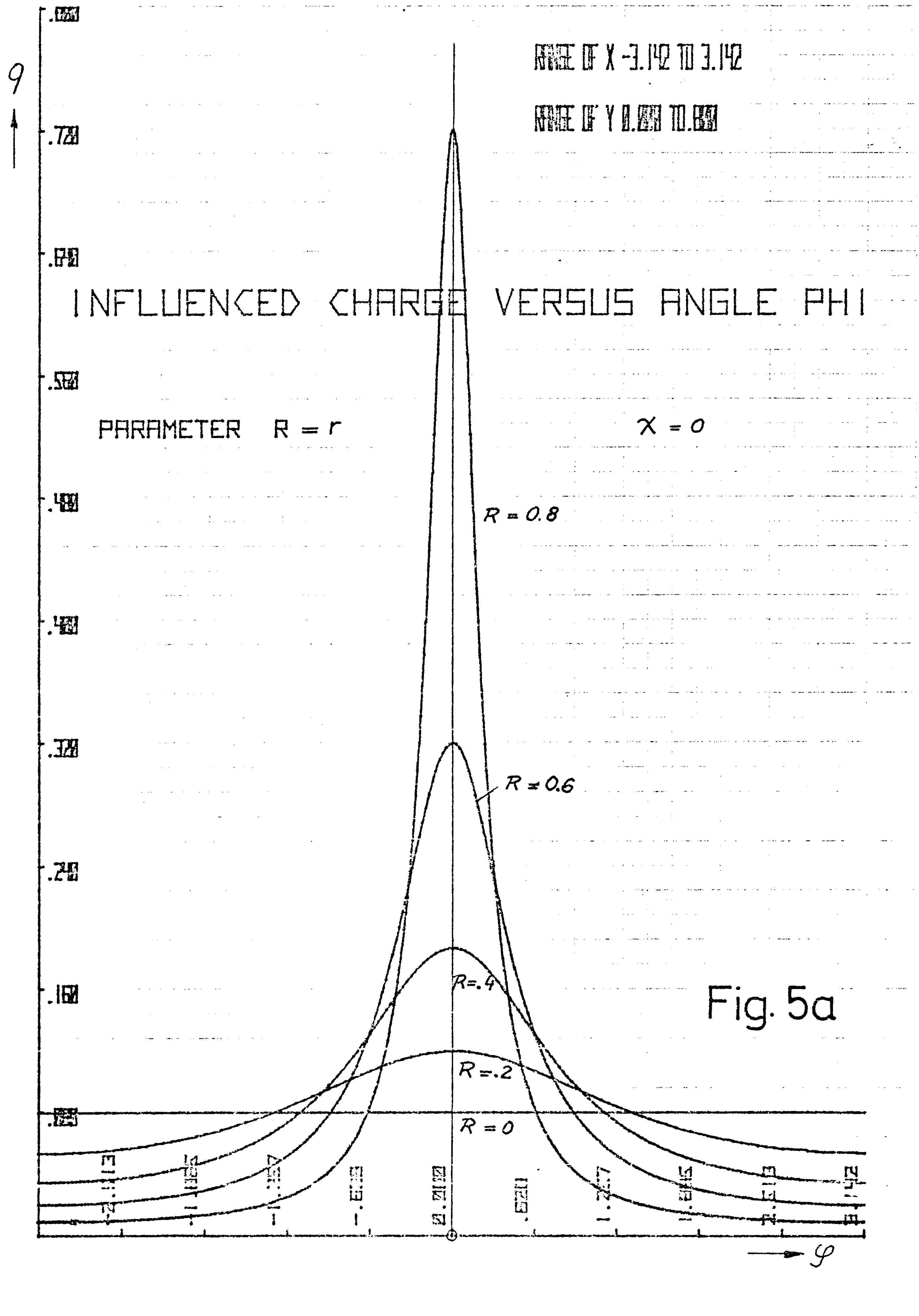

q
INFLUENCED CHARGE VERSUS ANGLE PHI
PARAMETER R = r
X = 0
R = 0.8
R = 0.6
R=.4
R=.2
R = 0
φ

Fig. 5a

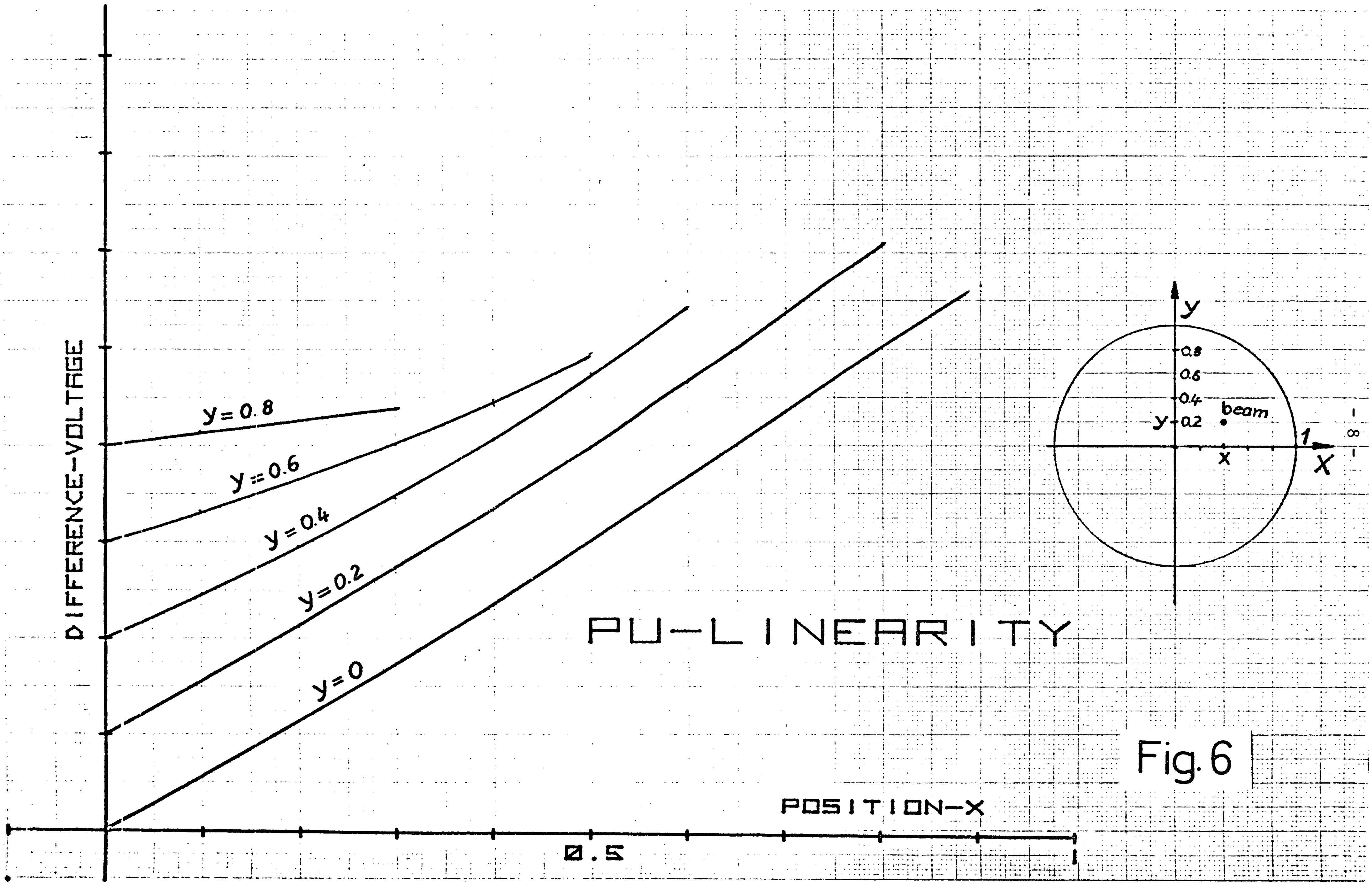

PU-LINEARITY
DIFFERENCE-VOLTAGE
POSITION-X
0.5
y = 0.8
y = 0.6
y = 0.4
y = 0.2
y = 0
y
X
0.8
0.6
0.4
0.2
beam
x
1

Fig. 6

Furthermore the sum of the signals

$$\sum_{\nu=0}^{3} U_\nu = \text{const.}$$

is independent of the beam position. Hence the linearity of the difference signals equals the linearity of the beam position signals

$$\frac{\Delta U}{\Sigma U} .$$

The signals generated at the four resistors propagate around the circumference. If we now eliminate the inphase components (corresponding to the intensity signal) and consider only the difference signals (cp. fig. 7),

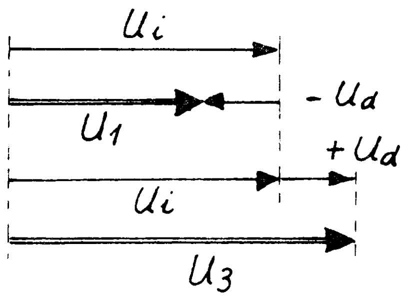


Fig. 7

we find opposite voltages U_d across opposite resistors (see fig. 8a).

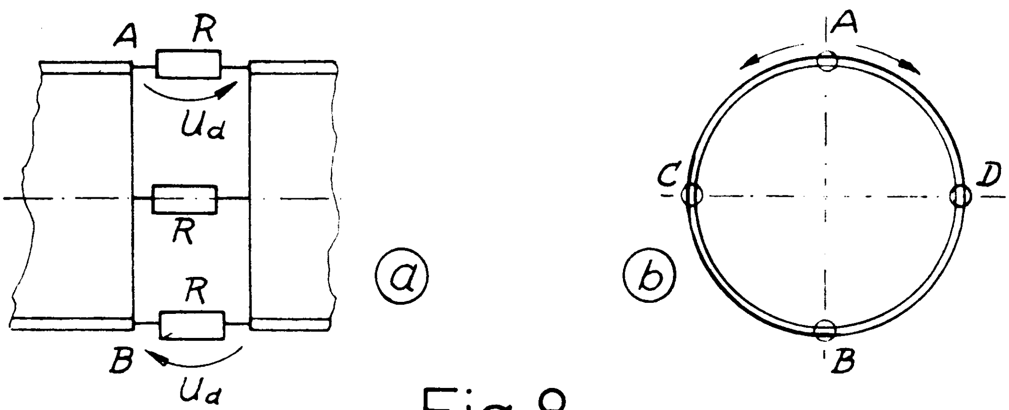


Fig.8

These signals travel in the transverse beam direction in two ways along the gap. (From point A via C to B and via D to B for example (Fig. 8b)).

What is the difference signal ΔU versus time? This has been studied with an analog model (cp. fig. 9).

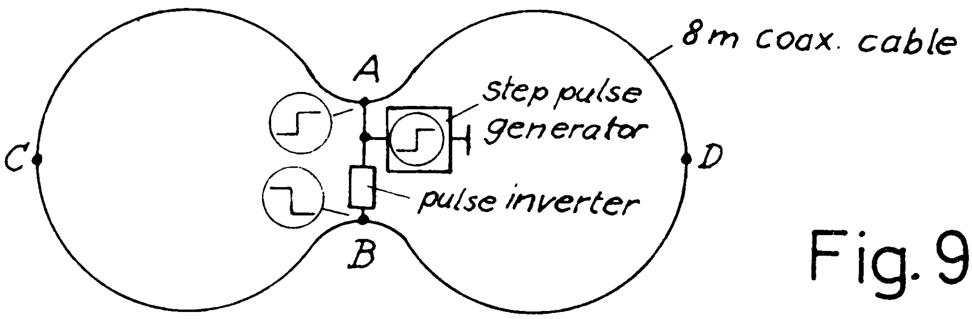


Fig. 9

The opposite signals were produced with a step pulse generator (EH 122) and a pulse inverter (transformer) and injected at points A and B into the closed loop of 8m coaxial cable.

If the transverse gap line (coax. cable) is not matched terminated, the difference signal between points B and A shows reflexions. Fig. 10 corresponds to the case $R > \frac{Z}{2}$ (2 cables of impedance Z parallel).

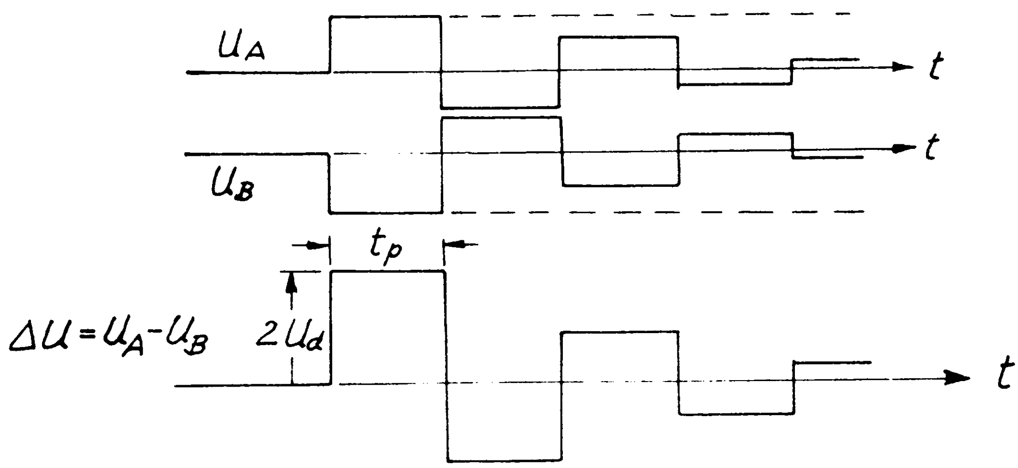


Fig. 10

Until the signals have travelled to the opposite side (delay t_p) the difference signals is

$$\Delta U = 2\,U_d \qquad (t < t_p) \tag{9}$$

The signals are then partially reflected and travel back to their origins where they are once more reflected and so on. The "life time" of the reflections depends on the reflection coefficient

$$\rho = \frac{2R - Z}{2R + Z} \tag{10}$$

These reflections cannot be observed in the sum signal as they are complementary and cancel.

Resistors put at symmetrical points C and D (for the measurement of the other coordinate) have no influence on the signals U_d travelling from A to B and vice-versa. The signals at points C and D (coming from A and B) are always cancelled due to symmetry. Hence no reflections occur due to these resistors.

If the two parallel lines from A to B are matched terminated, e.g.

$$R = \frac{Z}{2} \tag{11}$$

the difference signal ΔU appears as shown in fig. 11.

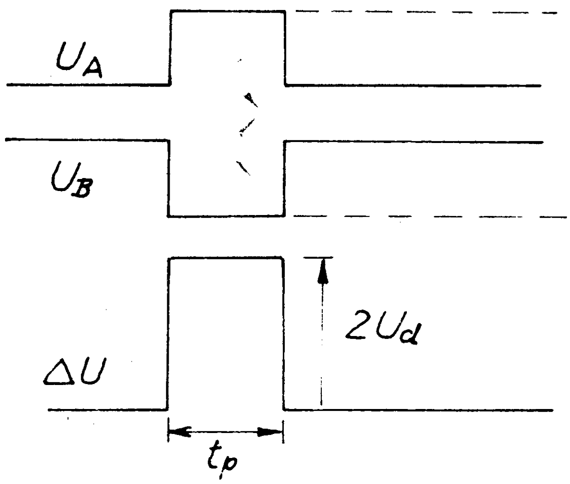


Fig.11

The difference signal

$$\Delta U = 2\, U_d \text{ for } t < t_p . \qquad (12)$$

The signal disappears after the propagation time t_p.

In order to obtain long difference signals ΔU, the propagation time t_p must be a maximum.

$$t_p = \tau \cdot \ell = \sqrt{L'C'} \cdot \ell = \sqrt{\varepsilon_o \varepsilon_r \mu_o \mu_r} \cdot \ell = \tau_o \sqrt{\mu_r \varepsilon_r} \cdot \ell \qquad (13)$$

(ℓ = half circumference of the vacuum chamber

$\varepsilon_o \varepsilon_r$ = absol. dielectric constant

$\mu_o \mu_r$ = absol. permeability

L' line inductance }
C' line capacitance } per unit length)

$\tau_o = \frac{1}{c}$ = 1/velocity of light

This means, if the diameter of the vacuum chamber is given (and cannot be increased) one should increase the relative dielectric constant ε_r and / or the relative permeability μ_r of the transverse gap line.

What happens to the position signal ΔU when the rise time τ_r of the signals U_d is greater than the propagation time t_p? It is evident that ΔU becomes smaller, but the integral

$$\int_0^{t_p+\tau_r} \Delta U dt = 2\int_0^{t_p} U_d\, dt = 2\, U_d \cdot t_p = F_1 = F_2 = F \qquad (14)$$

remains independent of the risetime. This is demonstrated on fig. 12 for $\tau_r = 2\, t_p$ (for the matched case).

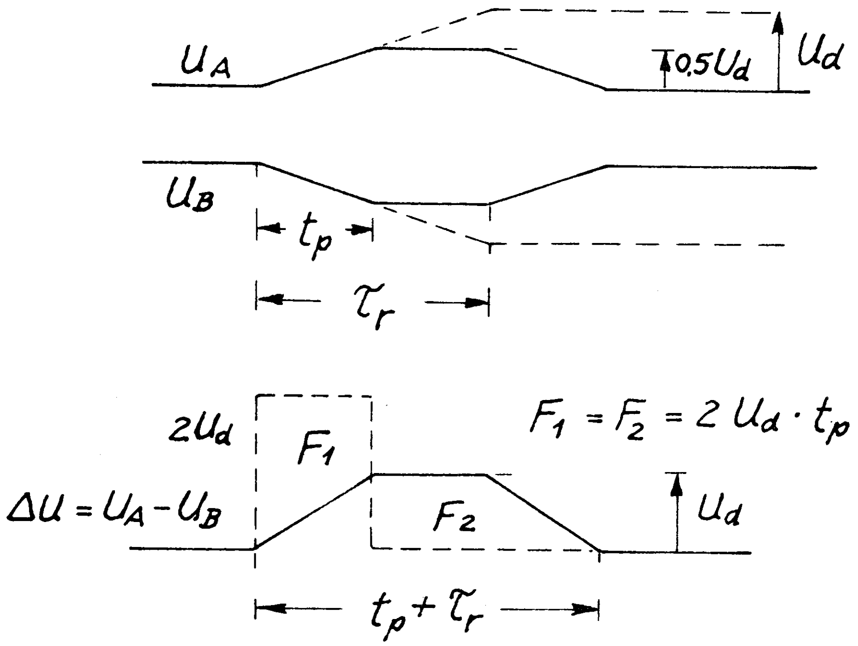


Fig.12

What is the match condition for the gap line? For a high dielectric constant ($\varepsilon_r >> 1$) of the gap material, the gap capacity can be calculated for the case where the cross-section of the insulator has the same dimensions as the vacuum chamber (the electric field is concentrated in the dielectric):

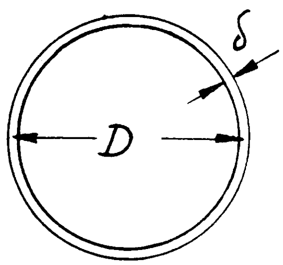


Fig.13

$$C = \frac{F \cdot \varepsilon_o \varepsilon_r}{d} \tag{15}$$

(d = gap length

F = D π δ (see fig. 13))

The line capacity per unit length

$$C' \approx \frac{C}{D\pi} = \frac{\delta\, \varepsilon_o \varepsilon_r}{d} \qquad (16)$$

From equation (13)

$$L' = \frac{\tau^2}{C'} = \frac{\tau_o^2\, \mu_r \cdot \varepsilon_r}{C'} \qquad (17)$$

Furthermore, the characteristic impedance of the gap line

$$Z_g = \sqrt{\frac{L'}{C'}} \qquad (18)$$

Combining equ. (16) to (18) yields the thickness of the gap insulator

$$\delta = \frac{\tau \cdot d}{Z_g\, \varepsilon_o \varepsilon_r} = \frac{\tau_o \cdot d \cdot \sqrt{\mu_r}}{Z\, \varepsilon_o \sqrt{\varepsilon_r}} \qquad (19)$$

Example : $Z_g = 50\ \Omega$; $\mu_r = 1$; $\tau_o = \frac{1}{c} = 3{,}3\ \frac{ns}{m}$

$d = 1$ mm; $\varepsilon_r = 8$ (iron sealing glasses)

$$\delta = \frac{3{,}3 \cdot 10^{-9}\ s}{50V \cdot m} \cdot \frac{0{,}1\ cm \cdot A \cdot 3{,}6\ \pi \cdot Vcm}{As \cdot \sqrt{8}}$$

$\underline{\delta = 2{,}64\ mm}$

The total gap capacity from equ. (15)

$$C = \frac{D\pi\delta \cdot \varepsilon_o \varepsilon_r}{d} = \frac{5 \cdot \pi \cdot 0{,}264 \cdot 10^{-12} \cdot 8}{0{,}1 \cdot 3{,}6\ \pi} \qquad (20)$$

$\underline{C = 3{,}67\ pF}$

leads with 4 parallel resistors R = 50 and the 4 necessary transmission lines of impedance Z = 50 Ω to the high frequency limit (equ. (3)) of the sum signal

$$f_H = \frac{1}{2\pi R_p C} = \frac{8}{2\pi \cdot 50 \cdot 3{,}67 \cdot 10^{-12}} \qquad (21)$$

$$\underline{f_H = 6{,}95 \text{ GHz}}$$

which is significantly above the required frequency of 2 GHz.

The assumed gap length d = 1 mm gives, for a beam with a rise-time τ_r = 1 ns and a velocity of about 10 mm/ns, a sufficiently good resolution.

5. Combined Intensity and Position PU

Fig. 14a shows the principle. The signals appearing across the 4 gap resistors R are transmitted by 4 coaxial lines of impedanze Z to a point where the intensity signal is produced by 4 summing resistors R1. The signals are rectified (by fast diodes D) with a charging time constant:

$$T_C = R_2 C \qquad (R_2 >> R1) \tag{22}$$

and a discharge time constant

$$T_D = R_i C \qquad (R_i >> R_2) \tag{23}$$

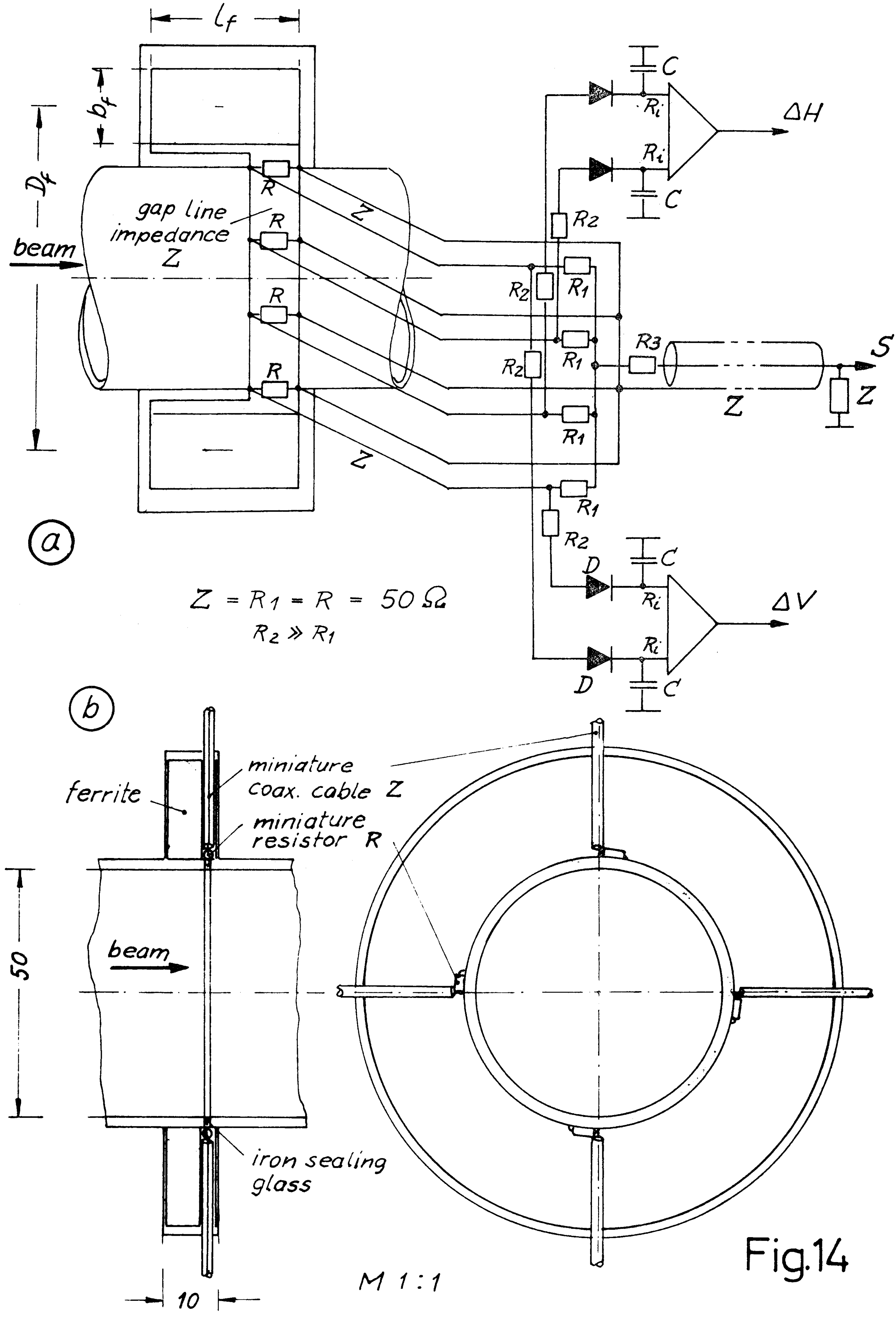
The position signals ΔV and ΔH are then produced by differential amplifiers.

5.1 Dimensions

The required inductance of the ferrite core is from equ. (4) with f_L = 1,59 MHz (§ 3) and $R_p = \frac{R}{4} = \frac{50}{4}$ (cable impedance neglected)

$$L = \frac{R_p}{2\pi f_L} = \frac{50}{4 \cdot 2\pi \cdot 1{,}59 \cdot 10^6} \tag{24}$$

$$\underline{L = 1{,}25\ \mu\text{H}}$$



l_f
b_f
D_f
beam
gap line impedance Z
R
R
R
R
Z
Z
C
R_i
ΔH
R_i
C
R_2
R_2
R_1
R_1
R_2
R_3
S
Z
Z
R_1
R_1
R_2
D
C
R_i
ΔV
R_i
D
C
a
Z = R_1 = R = 50 Ω
R_2 ≫ R_1
b
ferrite
miniature coax. cable Z
miniature resistor R
50
beam
iron sealing glass
10
M 1:1

Fig.14

The 1 turn inductance of a totoidal core is

$$L = \mu_o \mu_r \frac{b \cdot \ell}{\lambda} \qquad (25)$$

($b \cdot \ell$ = cross-section, $\mu_o \mu_r$ = permeability

λ = mean ferrite circumference)

The required rel. permeability μ_r is calculated from the specifications for the ferrite toroid given below

ℓ = 0,7 cm (total length of the PU = 1 cm)

b_f = 2 cm
$\lambda = D_f \cdot \pi = 7 \cdot \pi$ cm } (see fig. 14)

$$\mu_r = \frac{L \cdot \lambda}{\mu_o \cdot b_f \cdot \ell_f} = \frac{1{,}27 \cdot 10^{-6} \cdot 7\,\pi}{4\,\pi \cdot 10^{-9} \cdot 2 \cdot 0{,}7} \qquad (26)$$

$\underline{\mu_r = 1590}$

As ferrites with higher permeability exist, one could, if necessary, decrease the ferrite cross-section.

The gap line impedance Z_g, the 4 gap resistors R and the impedance Z of the connected cables have already been chosen in § 4.2

$\underline{Z_g = R = Z = 50\ \Omega}$

If $\underline{R_1 = Z = 50\ \Omega}$, the cables are matched for the difference signals. Fig. 14b shows the mechanical layout.

a) Intensity Signal

The equivalent circuit for the sum signal is shown in fig. 15.

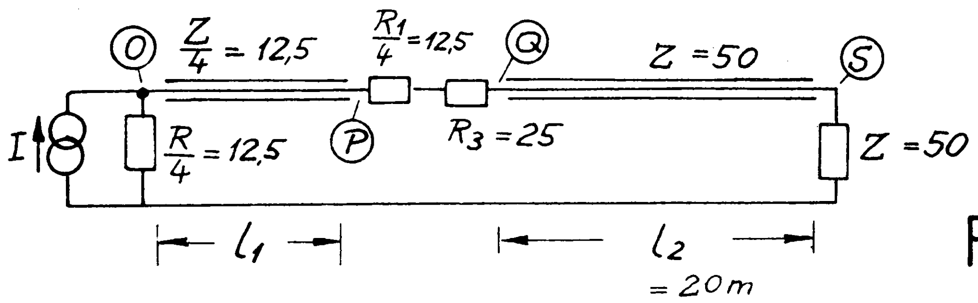


Fig.15

The resistor $R_3 = 25\ \Omega$ is inserted to absorb reflections coming back from the final termination Z of line ℓ_2. The reflections appearing at point P, due to the mismatch there, are absorbed in the source resistor $\frac{R}{4}$.

The input voltage

$$U_o = I \cdot \frac{Z}{8} \tag{27}$$

gives, compared with the output voltage

$$\frac{U_s}{U_o} = \frac{U_p}{U_o} \cdot \frac{U_Q}{U_p} \cdot \frac{U_s}{U_Q} \tag{28}$$

$$\frac{U_s}{U_o} = (1 + \rho) \cdot \frac{Z}{\frac{R_1}{4} + R_3 + Z} \quad \text{(cable losses neglected)} \tag{29}$$

with

$$\rho = \frac{Z + R_3 + \frac{R_1}{4} - \frac{Z}{4}}{Z + R_3 + \frac{R_1}{4} + \frac{Z}{4}} \tag{30}$$

$$\frac{U_s}{U_o} = \frac{2Z}{Z + R_3 + \frac{R_1}{4} + \frac{Z}{4}} \tag{31}$$

For the chosen values (see fig. 15); the input voltage equals the output voltage as :

$$\frac{U_s}{U_o} = 1 \tag{32}$$

This means, the max. sum output voltage is with I = 1,5 A and with equ. (27)

$$U_s = U_o = I \cdot \frac{Z}{8} = 1,5 \cdot \frac{50}{8} = \qquad (33)$$

$$\underline{U_s = 9,3\ V}$$

For the first 4 cables, the 50 Ω miniature cable RG 174 U (SUHNER) with length

$$\ell_1 \leq 1m$$

is proposed. It has a damping coefficient

$$a_1 = 1,8\ db/m \text{ at } 2\ GHz \qquad (34)$$

The transmission from point Q to S (ℓ_2 = 20 m, see fig. 15) can be performed by a 50 Ω 7/8" Flexwell cable which has a damping of

$$a_2 = 1,4\ db/20\ m \text{ at } 2\ GHz. \qquad (35)$$

Hence, the total attenuation at 2 GHz

$$\underline{a = a_1 + a_2 = 3,2\ db} \qquad (36)$$

b) Position Signal

The diodes are opened by the inphase components of the signal (see fig. 14) even when the beam is centered. The resistors R_2, which are much greater than the cable termination resistors R_1, determine the current flowing to the capacitors C.

What are the required values of R_2, C and R_i? An assumed upper frequency for the position detection

$$f_u = 500\ kHz$$

determines the discharge time constant

$$T_D = \frac{1}{2\pi f_u} = 318 \text{ ns} \tag{37}$$

The real charging of the capacitor takes place only during the time (see equ. (13))

$$t_p = \tau_o \sqrt{\varepsilon_r} \cdot \ell = \frac{3{,}3\text{ns} \cdot 283 \cdot 5{,}1\ \pi\ \text{cm}}{100\ \text{cm} \qquad 2} \tag{38}$$

$$\underline{t_p = 0{,}75 \text{ ns}}$$

Fig. 16 shows the stepwise charging of the condenser.

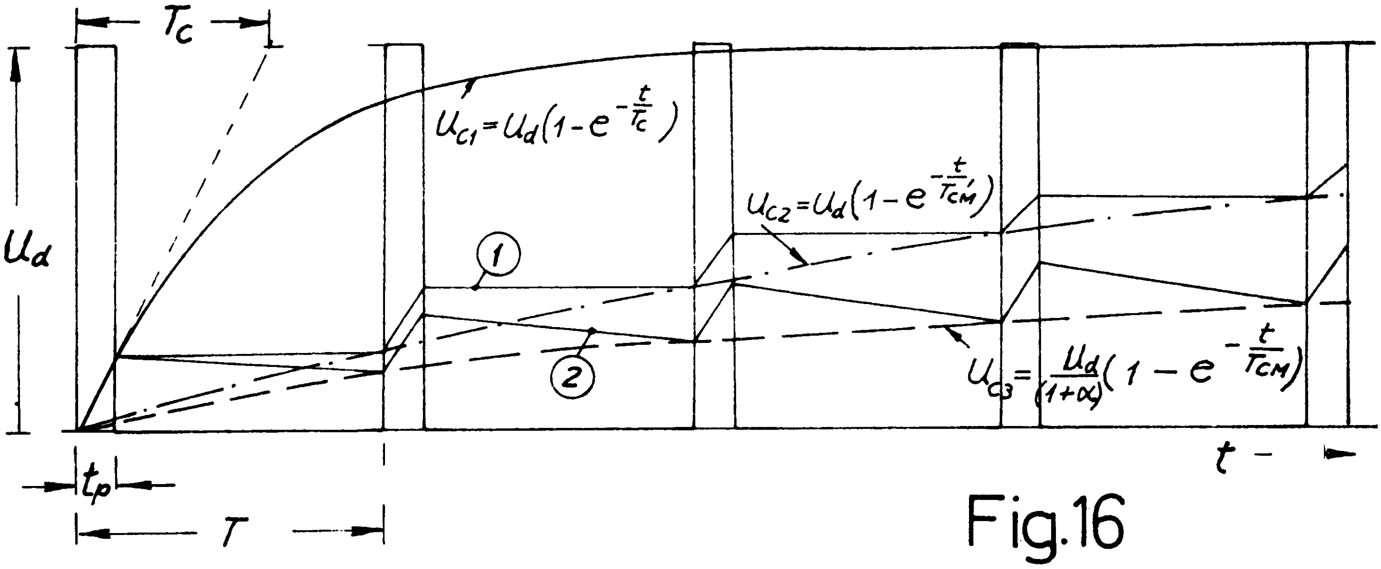


Fig.16

Without discharge between the pulses (curve (1)), the mean charging time-constant (from geometry)

$$T'_{CM} = T_C \cdot \frac{T}{t_p} \tag{39}$$

($T = \frac{1}{f} = 5\text{ns}$ = period, $T_C = R_2C$ = charging time constant during t_p).

With discharge between the pulses, the condenser U_C does not reach the voltage U_d. It saturates where the slope of (see fig. 16)

$$U_{C2} = U_d\ (1 - \exp(-\frac{t}{T_{CM}'})) \tag{40}$$

equals the negative slope of the discharging slope, e.g.

$$\frac{dU_{C2}}{dt} = \frac{U_{C2}}{T_D} \tag{41}$$

Combining the equ. (40) and (41) yields

$$t = T_{CM}' \, \ln \frac{T_{CM}' + T_D}{T_{CM}'} \tag{42}$$

Inserting t in equ. (40) gives the rel. saturation voltage

$$\frac{\hat{U}_{C3}}{U_d} = \frac{1}{1 + \frac{T_{CM}'}{T_D}} \tag{43}$$

and with equ. (33)

$$\frac{\hat{U}_{C3}}{U_d} = \frac{1}{1 + \frac{T_C T}{t_p t_D}} = \frac{1}{1 + \alpha} \tag{44}$$

where

$$\alpha = \frac{T_C T}{t_p T_D} \, . \tag{45}$$

The mean charging time constant with discharge between the pulses can be found by intersecting the tangent in the origin

$$U_t = \frac{t_p}{T_C} \left(1 - \frac{T}{T_D}\right) \cdot \frac{t}{T} \cdot U_d \tag{46}$$

with the asymptote

$$U_{as} = \frac{1}{1 + \alpha} \; U_d \tag{47}$$

This yields the mean charging time constant

$$t = T_{CM} = \frac{T\,T_C\,T_D}{(t_p\,T_D + T_C\,T)} \tag{48}$$

$$(t_p << T_C \text{ and } T << T_D)$$

From equ. (44) it can be seen that the time constant

$$T_C = R_2 C$$

must be minimum for a max. output signal $\hat{U}_{C3}$.

The proposed values are for $R_2 = 2\ k\Omega$

$C = 15\ pF$

and $R_i = \frac{T_D}{C} = \frac{318}{15} = 21{,}2\ k\Omega$

The following list shows a summary of the different time values in nano seconds.

T	$= 5$ ns	
t_p	$= 0{,}75$ns	(equ. (38))
T_D	$=318$ ns	(37)
T_C	$= 30$ ns	(49)
T_{CM}	$=123$ ns	(48)

The mean charging time constant T_{CM} = 123 ns is sufficiently small compared with the max. tolerable 318 ns (see equ. (37)).

What is the position sensitivity of the detector?

The rise-time of the 1 ns beam pulses is smaller than the propagation time t_p = 0,75 ns, but greater than zero. If we assume an equivalent pulse length

$$t_p' = \frac{t_p}{3}$$

the condenser C is charged to the max. value (see equ. (44))

$$\hat{U}_{3C} = U_{d\,max} \cdot \frac{1}{1 + \frac{T_C T \cdot 3}{t_p \cdot T_D}} =$$

$$\hat{U}_{3C} = U_{d\,max} \cdot \frac{1}{1 + 1,89} = 0,346\ U_{d\,max}$$

A peak beam current of $\hat{I} = 1,5$ A

generates a voltage

$$U_{d_{max}} = \hat{I} \cdot \frac{R}{4} = 1,5 \cdot \frac{50}{4}$$

$$U_{d_{max}} = 18,7\ V$$

This leads to a position sensitivity

$$S = \frac{U'_{3C\,max}}{x_{max}} = \frac{18,7V \cdot 0,346}{2,5cm}$$

$$\underline{\underline{S = 2,59\ \frac{V}{cm}}}$$

A position displacement of

$$\Delta x = 0,1\ mm$$

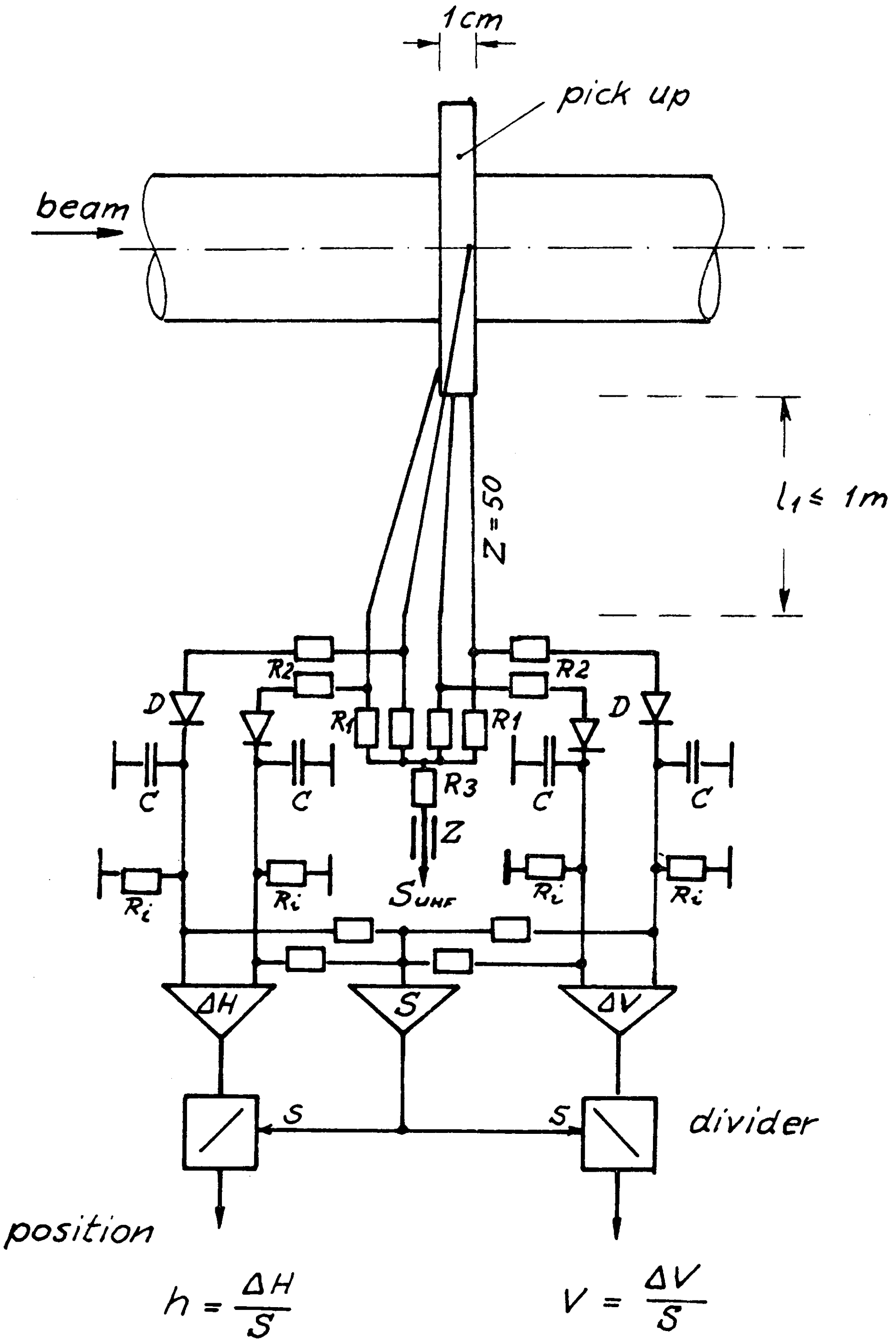
gives still a difference signal of

$$\Delta U_{0,1mm} = S \cdot \Delta x = 26\ mV$$

which is much higher than the input noise signal of the differential amplifiers (fig. 14).

The complete circuit including the normalisation to the beam intensity by two analog dividers is shown in fig. 17.

UHF Wide Band PU Station with Position Measurement



Z = 50
R1 = 50
R2 = 2k
R3 = 25
R_i = 21.2 k
C = 15 pF

Fig. 17

6. Costs

The following list gives the estimated prices

	Fr.S.
- 20 m coaxial cable 7/8" 50 Ω (Flexwell)	350,--
- ferrite core	100,--
- 2 coax. connectors (Radial PQR)	400,--
- insulated vacuum chamber	300,--
- mechanical pieces	100,--
- 4 miniature resistors	50,--
- electronics	2'500,--
2 differential amplifiers	
sum amplifier	
2 analog dividers	
power supply	
chassis	
- dividers	200,--
	Total 4'000,--

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Distribution : open

New Linac Working Party

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