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POSSIBILITIES OF TEMPERATURE-EFFECT BEAM MONITORS FOR THE SLOWLY EJECTED BEAM OF THE C.P.S.

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SUMMARY

A survey of some thermal effects is given. Since direct conversion into electrical output signals seems to be most attractive, the discussion is limited to two such cases: 1. Beam monitor utilizing the effect of thermal resistance change, and 2. Thermo-couples in the proton beam. Problems of temperature distribution and cooling time constants are mentioned, as well as the electrical read out.

Two examples are calculated in detail. First, a 10 cm long, 0.05 mm diameter platinum wire with ten zigzags of 1 cm length in the x - z plane (or y - z plane) is suggested. Heating the wire with about 50 mA electrically to 100° C, we achieve an effective thermal cooling time constant (mostly radiation) of approximately 1 sec. The wire temperature yielding the most accurate results can be found experimentally by adjusting the d.c. current. The electrical read out employs a differential amplifier which input is based on a difference method with a reference resistor yielding about 0.5% accuracy.

Second, the use of thermo-couples is investigated. The output signal is only about 1 mV (compared to 8 mV for the resistance change system) and we do not have a simple way of adjusting the time constant. In addition, the system is sensitive to position changes in x and y direction simultaneously, which makes the overall method inferior to the platinum wire monitor.

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I. INTRODUCTION

The proton beam of the CERN PS interacting with materials deposits energy and causes a temperature rise. This effect can be utilized to measure the beam intensity, position, profile and duration. The following list summarizes some of these effects:

1. Electrical Effects

a) Change of electrical resistance

b) EMF produced in thermo-couples

c) Change in dielectric constant

d) Change in permeability

e) Change of transistor gain

f) Change of electrolytic potential.

2. Mechanical Effects

a) Expansion of solids, liquids and gases

b) Change in mechanical properties of solids.

3. Electromagnetic Radiation

a) Radiation in infra-red or visible spectrum.

4. Chemical Effects

a) Change in chemical reaction time (catalyst)

b) Change of colour

c) Decomposition of chemicals.

5. Biological Effects

a) Change in rate of growth

b) Variation in exchange rate of chemicals in plants and animals.

6. Kinematic Effects

a) Brownian motion of molecules (origin of most other effects).

7. Quantum Mechanical Effects

a) Permanent changes in lattice structure

b) Temporary changes in lattice structure.

We prefer output signals which are based on one single and linear temperature effect. We would also like a very direct observation of the primary effect. Since the information has to be transmitted to distant points, electrical signals seem to be well suited. Examining point 1., we find that change in electrical resistance and thermo-couples fulfill quite well the above conditions. Many other methods seem, at first glance, attractive, but often forced cooling is required to achieve a thermal time constant of 0.5 sec. This report will discuss only two methods, namely, the effect of electric resistance change and the use of thermo-couples.

II. BEAM MONITOR USING THE EFFECT OF THERMAL RESISTANCE CHANGE

1. Principle of Operation

If we measure the electric resistance of a suitable material before and after the proton beam passed through, the resistance change is a measure of the beam intensity at that position. Using material in the form of a thin wire enables us to determine the beam profile.

2. Choice of Material

We are looking for a material with a high electric temperature coefficient α, and a reasonably high specific resistance ρ. In addition, we require radiation and corrosion resistance. Gases and fluids have to be enclosed by containers, which themselves absorb protons, yielding a complicated temperature distribution.

Recent experiments at SLAC[1] showed that some thermistors are surprisingly radiation resistant. Fenwall bead thermistors were irradiated by 70 MeV electrons. After 10^{13} erg/g a slight change in resistance was detected. Since the exact data of that experiment are still missing and the general problems discussed in this report are valid for any material, we keep this possibility open for future experiments.

In order to give a specific example, we look further for suitable materials and find from the metals the following elements:

	α(electr.temp.coeff.)
iron (at 20° C)	0.005
bismuth	0.00446
platinum	0.003 .

We have chosen platinum for its superior purity and corrosion resistance.

3. Geometry of the System

The dimensions of the monitor depend widely on the position in the beam. If we desire to measure intensity, position and profile, we require high accuracy of the mechanical dimensions.

The shape of the sensor could have any cross-section, preferably a large surface area for faster cooling. For reasons of simplicity, we suggest a round wire (0.05 mm diameter). Since the total absorbed energy depends on the wire mass and the intersection of the beam, we suggest an arrangement as sketched in Fig. 1 . This configuration has the advantage of increasing the total electric resistance and thus reduces some contact problems. The length L of the system is limited by the convergence (or divergence) of the beam. Worst case considerations[2] (in front of the target) yield a beam convergence of 8 mrad. If we desire a position accuracy of 0.1 mm, the greatest distance between the first and the last wire of the device should be less than 12 mm (Fig. 2).

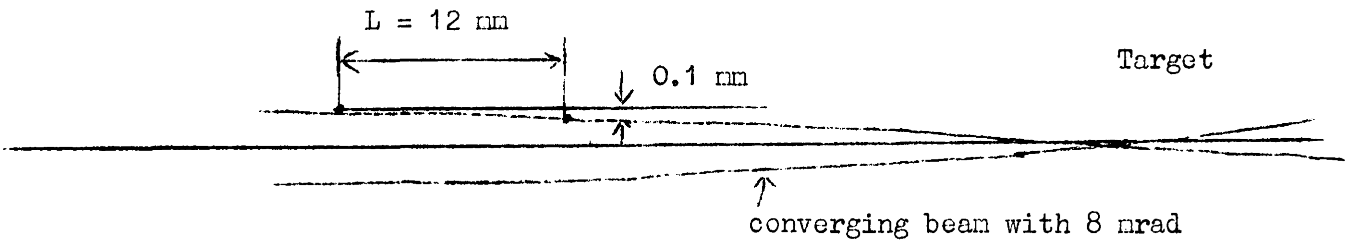


Fig. 2. Determination of the maximum length of the system.

4. Heat Production and Resistance Change by the C.P.S. Proton Beam in a Platinum Wire

The C.P.S. proton beam with an assumed energy of 27.5 GeV, having a proton density of $D(x, y)$ in the wire, deposits a total energy E_{tot}. E_{tot} can be expressed by

$$E_{tot} = \rho \cdot \epsilon \cdot N_W \qquad (1)$$

ρ = area density of the wire

ϵ = ionization energy/ area density and 1 proton

N_W = number of protons penetrating through the wire.

As an example, we consider a platinum wire diameter of 0.05 mm. The density per unit area of a wire can be averaged to be

$$\rho = \frac{\delta}{d\,l} = \frac{d^2 \pi\, l\, \delta}{4\, d\, l} = \frac{d\pi\,\delta}{4} \quad [gm/cm^2] \qquad (2)$$

δ = specific density of platinum = 21.4 g/cm^3

ϵ = 1.451 $MeV/gm/cm^{-2}$ for 27.5 GeV protons in lead*).

*) The energy absorption coefficient for platinum could not be found and the value for lead was taken instead. This yields a pessimistic result.

The average energy absorbed in the wire becomes:

$$\left.\begin{aligned} \bar{E}_{tot} &= \rho \cdot \epsilon \; N_W = \frac{d \pi \delta}{4} \; \epsilon \; N_W \\ \bar{E}_{tot} &= \frac{5 \times 10^{-3} \; \pi \times 21.4 \times 1.45}{4} N_W = N_W \times 0.122 \text{ MeV} \end{aligned}\right\} \quad (3)$$

We now have to find the number of protons N_W penetrating into the wire. Appendix I shows the assumptions made to arrive at $N_W = 1.3 \times 10^{10}$ protons/p in the centre of the beam. Therefore

$$\bar{E}_{tot} = 0.122 \times 1.3 \times 10^{10} = \underline{1.6 \times 10^{9} \text{ MeV}}$$

since $1 \text{ eV} \equiv 3.82 \times 10^{-20}$ cal.

The energy Q absorbed in the wire is $\underline{Q = 6.1 \times 10^{-5} \text{ cal.}}$

Figure 3 shows the approximate heat and temperature distribution in the wire accepting the assumption in App. I.

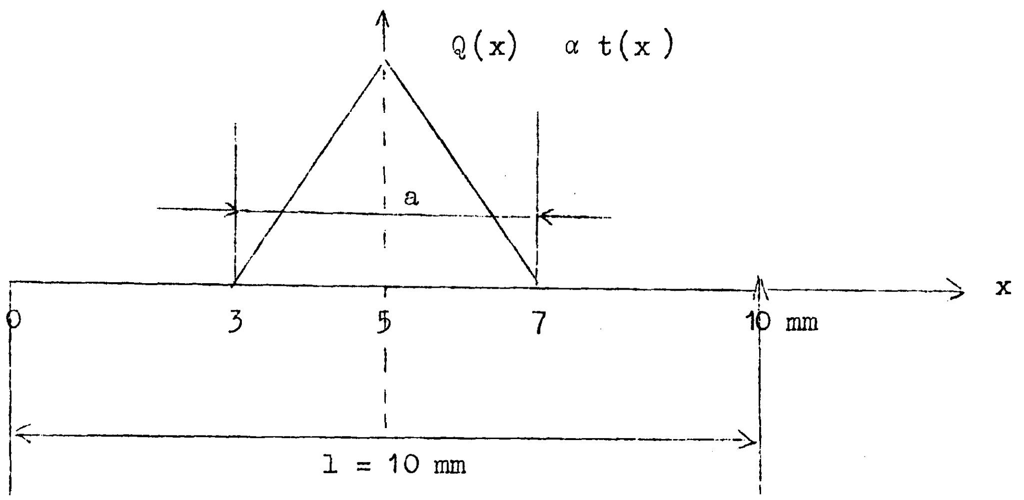


Figure 3 : Approximate App.I) heat distribution in a platinum wire of 10 mm length and a beam diameter of 4 mm.

The initial temperature distribution can be written as:

$$\Delta t(x) = \frac{\Delta Q(x)}{c_p W} \qquad (4)$$

$\Delta t(x)$ = temperature rise as function of x

$\Delta Q(x)$ = heat increase as function of x

c_p = specific heat of platinum = 0.0324 cal/g° C

W = weight = δ = $r^2 \pi l \delta = 1.7 \times 10^{-4}$ (for l = 4 mm).

The average temperature rise of the wire along the beam diameter (4 mm) is:

$$\Delta t = \frac{\Delta Q}{c_p W} = \frac{6.1 \times 10^{-5}}{0.0324 \times 1.7 \cdot 10^{-4}} = \underline{11^\circ \text{ C.}}$$

This results in a resistance change of

$\Delta R = \alpha \Delta t$

α_{Pt} = 0.003 Ω/°C (Platinum at 40° C to be considered constant over small Δt).

$\underline{\Delta R}$ = 0.003 × 11 = $\underline{.033 \text{ R}}$ or 3.3% of R_{tot} .

Since $R = \rho \frac{l}{A}$ $\rho = 10^{-5}$ Ω cm

l = 1 cm

A = 2×10^{-5} cm²

$$\underline{R} = \frac{10^{-5} \times 1}{2 \times 10^{-5}} = \underline{0.5\ \Omega} \text{ per 1 cm wire.}$$

Thus $\underline{\Delta R}$ = 0.5 Ω × 0.033 = $\underline{.0165\ \Omega \text{ per 1 cm wire}}$.

Considering Fig. 1 with 10 cm wire, we have:

$R_{tot} = 5\ \Omega$

$\Delta R_{tot} = 0.165\ \Omega$.

This resistance change corresponds to the maximum signal possible with 6×10^{11} p/p and 4 mm beam diameter.

For profile measurements we would like to detect at least 1/10 of the peak value. In addition, we tolerate a beam intensity change of a factor of ten (down to 6×10^{10} p/p). This reduces the resistance chance by a factor of 100 to 0.035% R. The small change of R indicates that direct measurement of R is difficult, and therefore null or difference methods should be employed to measure it. We shall discuss the read-out methods later.

5. Choice of Electrical Values and Accuracy

The voltage signal output depends on the maximum possible current I we can pass through the wire (Fig. 6)

$$V_0 = I\,(R_s - R_r) \tag{5}$$

The current I is limited by the I^2R heating. In addition, we can regulate the time-constant with the current, varying the temperature gradient to the surroundings. Let us assume we heat the wire to $t_{ambient} + 80^\circ$ C $\cong 100^\circ$ C. The heat balance can be written as: (considering only convection and radiation):

$$I^2 R C = h S \Delta t_e + \sigma \epsilon F S \left(T_1^4 - T_2^4 \right) \tag{6}$$

I = unknown current (chosen to obtain $\sim 100^\circ$ C wire temperature)
R = resistance of 1.0 cm wire = 0.5 Ω
C = conversion factor = 0.239 cal/ws
S = cooling surface = $d\pi l$
Δt_e = temperature rise due to heating
h = thermal convection factor.

h was found in Jakob[5] to be :

$$h = \frac{0.4\ k}{l}\ (1)^{\text{App.II)}} = \frac{0.4 \times 62 \times 10^{-6}}{1\ \text{cm}} = 24.8 \times 10^{-6}\ \text{cal}/{}^{\circ}\text{C sec cm}^2$$

k_{air} = 62×10^{-6} cal/cm sec $^{\circ}$C

l = 1 cm

σ = 1.376×10^{-12} cal/sec^{-1} cm^{-2} $^{\circ}$K^{-4}

S = effective radiating area 6.28×10^{-3} cm^2

ϵ = emission efficiency for Platinum $\cong$ 0.9

F = shape factor = 1, assuming no reflection

T_1 = 373° K

T_2 = 293° K.

We solve equation (6) for the current I and obtain

$$I = \sqrt{\frac{h\ S\ \Delta\ t_e + \sigma \epsilon\ FS\ (T_1^4 - T_2^4)}{R\ C}} \qquad (8)$$

$$I = \sqrt{\frac{3.14 \times 10^{-5} + 2.58 \times 10^{-4}}{0.12}} \qquad \cong 50\ \text{ma} \qquad (9)$$

We realize that the radiation term is an order of magnitude larger than the convection.

It follows from equation (5)

$$V_0 = 50\ \text{ma}\ \ 0.165\ \Omega = 8.25\ \text{mV}.$$

Using a chopper stabilized amplifier, such as the Philbrick SP 656, it is possible to obtain an accuracy of 0.5% , provided we can eliminate all other external noise sources.

6. Recovery Time-Constant

After every beam pulse, the temperature should decay to the ambient temperature t_0. The cooling time-constant should therefore be short compared to the time interval between the beam pulses, but long compared to the pulse length.

We need to calculate the dynamic heat distribution in the wire. In order to avoid long calculations we approximate the time dependent term with the time-constant τ and write the heat balance in form of a difference equation. Figure 4 shows the control volume.

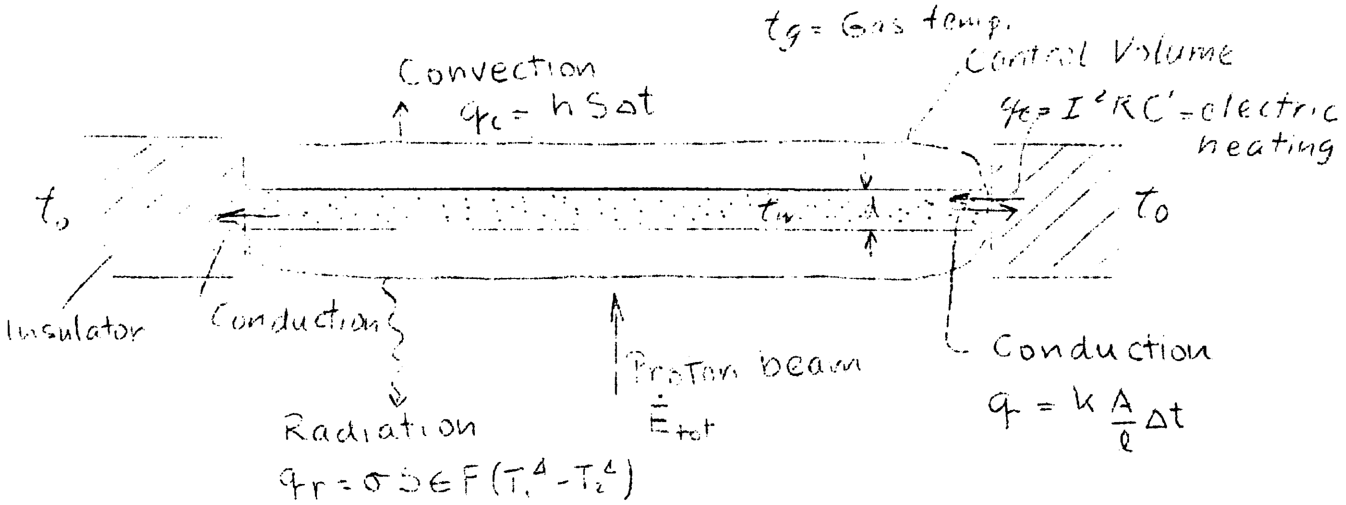


Figure 4 : Control Volume.

The general heat equation in words is:

rate of heat inflow - rate of outflow = increase in storage, or

$$\dot{E}_{beam} + I^2 R C - \frac{kA}{l} \Delta t_1 - hS \Delta t_2 - \sigma \epsilon F S (T_1^4 - T_2^4) = \rho c V \frac{\Delta t}{\Delta \tau} \quad (9)$$

$\dot{E}_{beam}$ = Energy rate deposited by proton beam

$I^2 R C$ = Electric heating

- I = d.c. current
- R = wire resistant
- C = conversion constant.

$\frac{kA}{l} \Delta t_1$ = conduction along the wire

- k = thermal conduction of platinum
- A = wire cross-section
- l = wire length
- Δt_1 = temperature difference between wire and insulator $\Delta t_1 = t_w - t_0$

$hS \Delta t_2$ = convective heat transfer

- h = convective transfer coefficient
- S = effective cooling area
- Δt_2 = temperature difference between wire and gas $\Delta t_2 = t_w - t_g$

$\sigma \epsilon F S (T_1^4 - T_2^4)$ = radiation heat transfer

- σ = Boltzmann constant
- S = radiatating area
- F = shape factor
- T_1 = wire temperataure in ^{o}K
- T_2 = gas or container temperature in ^{o}K
- ϵ = emission efficiency

$\rho c \frac{\Delta t}{\Delta \tau}$ = heat storage

- ρ = density of platinum
- c_p = specific heat
- V = wire volume
- $\Delta \tau$ = time constant (as defined in Fig.5).

We define the time τ_0 as the end of the beam burst. The initially sharply peaked temperature distribution will soon become flat, due to thermal conduction. We thus assume a rectangular temperature distribution with the dimension of $t_{max/2}$ and the length of a beam diameter = 0.4 cm. Since the ends of the wire are highly insulated, we neglect heat loss by conduction. Equation (9) reduces to:

$$I^2 R C - hS \Delta t - \sigma \epsilon SF (T_1^4 - T_2^4) = \rho c \frac{\Delta t}{\Delta \tau} \qquad (10)$$

Solved for $\Delta \tau$, we obtain:

$$\Delta \tau = \frac{\rho c \quad \Delta t}{I^2 R C - hS \Delta t - \sigma \epsilon S F (T_1^4 - T_2^4)} \qquad (11)$$

Substituting the proper values, the above equation yields:

$$\underline{\Delta \tau \cong 1 \text{ sec.}}$$

The following picture (Fig.5) shows an approximate temperature pulse in the wire, in function of time τ.

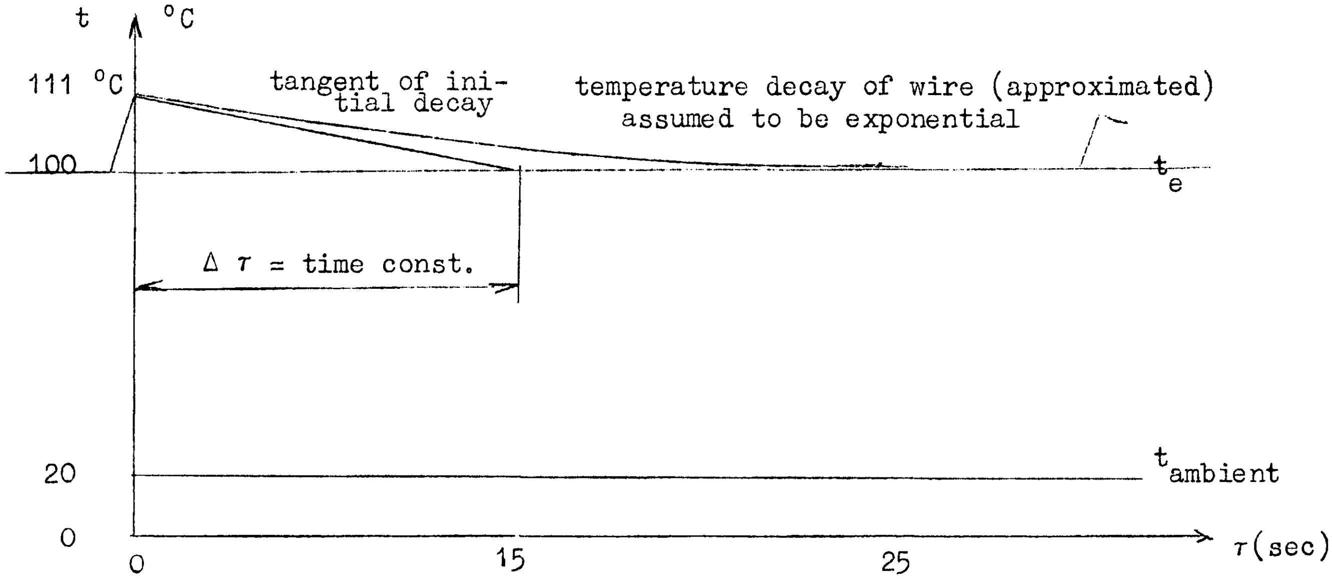


Figure 5 : Time dependent temperature distribution.

Considering the crude approximations used in this calculation, the time constant of about 1 sec indicates only that we are in the right order of magnitude. The d.c. current should experimentally be adjusted so that less than 0.5% of the output voltage is present before the new beam pulse starts.

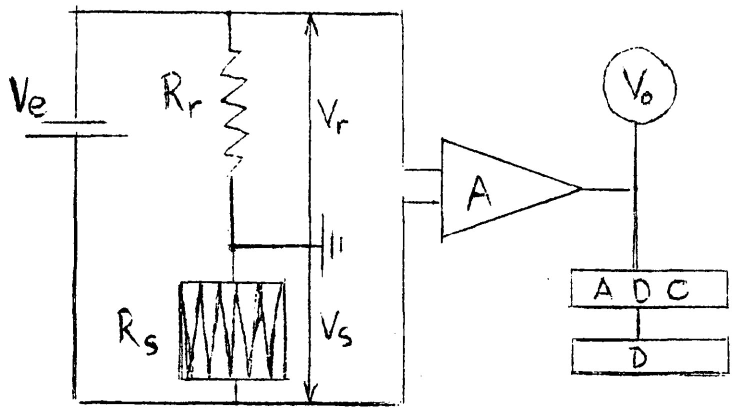
7. Electrical Measurement

We consider two different ways of measuring the resistance change of the wire.

a) Bridge compensator.

b) Difference amplifier.

The conventional bridges are mechanically balanced. The time constants are long compared with the short rise time of our pulse, and are thus not suited for our problem. A difference amplifier could be employed, placing a reference resistor in the same container with the sensor. We can match the resistors to about $10^{-4}\ \Omega$. It should then be possible to read an accuracy of 0.5% of ΔR.



V_e = Voltage source
R_r = Reference resistor
R_s = Measuring resistor
V_r = Reference voltage
V_s = Measuring voltage
A = Gain of difference amplifier
ADC = Analogue to Digital converter
V_o = Analogue output voltage
D = Digital output.

Figure 6.

8. Discussion

Calculations in the previous chapters showed that a beam monitor with platinum wire is an accurate tool to measure the beam profile. It is, however, important to have a time constant which is relatively long compared to the pulse length (up to 200 msec) and short compared to the repetition rate of the beam pulse (~2.5 sec). The suggested method has the advantage of being able to adjust the time constant experimentally by changing the d.c. current through the wire and thus matching the temperature for proper cooling. For very slowly ejected pulses (> 50 msec) a calibration curve will be necessary to compensate for cooling during the beam pulse.

III. BEAM MONITOR USING THERMO-COUPLES

Instead of putting a wire in the beam, we mount thermo-couples, e.g., according to Fig. 7. The thermo-electric force is created at the last point of connection by the two metals. Thus, the read-out voltage depends only on the temperature at this point. The temperature distribution in the leads and in the junction is much more complicated than in the platinum wire system. In addition, the temperature distribution is sensitive to the beam position in x and y direction (Fig. 8) and even two symmetrically placed thermo-couples cannot completely compensate for this effect. A Pt.Rd-Pt. thermo-couple delivers about 0.5 mV for 10° C temperature difference. Having two thermo-couples placed in series, yields 1 mV signal (positioned in the beam centre at 6×10^{11} p/p). Since the mechanical dimensions are very similar, using the miniature thermo-couples by Philips (0.005 cm Ø), we can compare the cooling time constant with the previous calculations. In the first case, most of the energy was lost by radiation. In this example, at low temperatures of $\sim 30^\circ$ C ($\Delta t = 10^\circ$ C), the time constant must be much longer because of the fourth power law of radiation. In order to achieve the desired time constant, we have to employ forced cooling or a helium atmosphere. Forced cooling could be gated in bursts, after the beam pulse, so that the measurement is not disturbed. Figure 9 shows a block diagram of such an arrangement.

IV. COMPARISON OF THE RESISTANCE MONITOR AND THE THERMO-COUPLE MONITOR

	Resistance monitor	Thermo-couple monitor
Material	platinum	Pt.Rd - Pt.
Temperature rise (at 6×10^{11} p/p in)	~ 10° C	~ 10° C
Output signal	8 mV (10 cm wire)	1 mV (2 therm.-coup.)
Accuracy	0.5%	< 0.5%
Time constant	~ 1 sec (100° C) adjustable	≫ 1 sec (30° C) forced cooling or He coolant necessary
Life-time	∞	$> 10^{23}$ n v t (unknown for protons)
Amplifier	differential	differential
Temperature of sensor	~ 100° C (heated with ~ 50 mA)	~ 20° C

Considering the above data, we can conclude that the resistance monitor is superior to the thermo-couple monitor. If we can use thermistors in the future, the choice is even more in favour of the resistance monitor.

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ACKNOWLEDGEMENTS

I would like to express my thanks to K.H. Reich, C. Bovet, Ch. Fabjan and J. Mann for many stimulating discussions.

Distribution (Open):
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APPENDIX I

We define the horizontal and vertical beam diameters so that the cross-sections contain 90% of the total beam intensity. The total number of protons can then be expressed as:

$$N = \frac{1}{0.9} \int_{-\frac{a}{2}}^{+\frac{a}{2}} \int_{-\frac{b}{2}}^{+\frac{b}{2}} (C\,x)\,y \quad dx\,dy \qquad (I.1)$$

If we approximate the beam profile by a triangle, (Fig. I.1) we obtain a two-dimensional picture in the form of a cone with elliptic cross-section. We can easily perform the integration yielding:

$$\underline{N} = \frac{1}{0.9}\,\frac{a\,b}{4}\,\frac{\pi\,h}{3} = \underline{\frac{ab\;h\;\pi}{10.8}} \qquad (I.2)$$

The above formula allows to normalize any beam intensity if the dimensions a and b of the beam are known.

For our particular case, we assume $a = b = 4$ mm and $N = 6 \times 10^{11}$ p/p.

This normalizes the maximum density h to:

$$h = \frac{N\;10.8}{ab\;\;\pi} = \frac{6 \times 10^{11} \times 10.8}{16\;\;\pi} = 1.1 \times 10^{11}\ \text{p/mm}^2$$

The number of protons penetrating through a 0.05 mm diameter platinum wire, positioned in the centre of the beam is :

$$N_{w/\mathbb{C}} = \frac{h \times d \times a}{2} = \frac{N \times 10.8\;d}{a\;\;\pi\;\;2}$$

$$\underline{N_{w/\mathbb{C}}} = \frac{6 \times 10^{11} \times 10.8 \times 0.05}{4\;\;\pi\;\;2} = \underline{1.3 \times 10^{10}\ \text{p/p}}\ .$$

2.2% of the total beam shall penetrate the wire.

APPENDIX II

In Jakob[4] we find the relation of cooling of long horizontal cylinders. He relates the Nusselt number (N_{Nu}) to the product of the Grashof number (N_{Gr}) times the Prandtl number (N_{Pr}).

$$\left.\begin{aligned} N_{Nu} &\stackrel{\Delta}{=} \frac{hD}{k} \\ N_{Gr} &\stackrel{\Delta}{=} \frac{g\,D^3\beta\,\Theta}{\gamma^2} \\ N_{Pr} &\stackrel{\Delta}{=} \frac{\nu}{\alpha} \end{aligned}\right\} N_{Gr}\,N_{Pr} = \frac{gD^3\beta\Theta\,\rho^2 c_p}{\mu\,k} \qquad \text{(II.1)}$$

g = Newton's constant of acceleration = 32 ft sec^{-2}

D = characteristic length = 0.005 cm = 1.64×10^{-4} ft

β = cubic coefficient of thermal expansion = 0.00367 $\frac{\Delta\vartheta}{^{\circ}C}$ = $2.04 \times 10^{-3}\ ^{\circ}F^{-1}$

Θ = temperature excess = 11 °C = 20° F

k_{air} = thermal conduction = $15 \times 10^{-3}\ \frac{Btu}{hr\,ft\ ^{\circ}F}$ = $4.17 \times 10^{-6}\ \frac{Btu}{sec\,ft\ ^{\circ}F}$

c_p = specific heat (air) = 0.24 cal $g^{-1}\ ^{\circ}C^{-1}$ = 2.65 Btu $lb^{-1}\ ^{\circ}F^{-1}$

ρ = density (air) = 1.29 g m^{-3} = 8.1×10^{-5} lb ft^{-3}

μ = viscosity (air) = $190 \times 10^{-6}\ cm^{-1}\ sec^{-1}$ = 1.275×10^{-5} lb $ft^{-1} sec^{-1}$.

This yields a $N_{Gr}\ N_{Pr}$ of <u>1.89×10^{-9}</u>.

Jakob states that for $(N_{Gr}\ N_{Pr}) < 10^{-5}$ the N_{Nu} approaches a constant value of about 0.4, so that the thermal convection coefficient becomes:

$$h \approx 0.4\ \frac{k}{L} \qquad \text{(II.2)}$$

Note that this equation is independent of the wire diameter.

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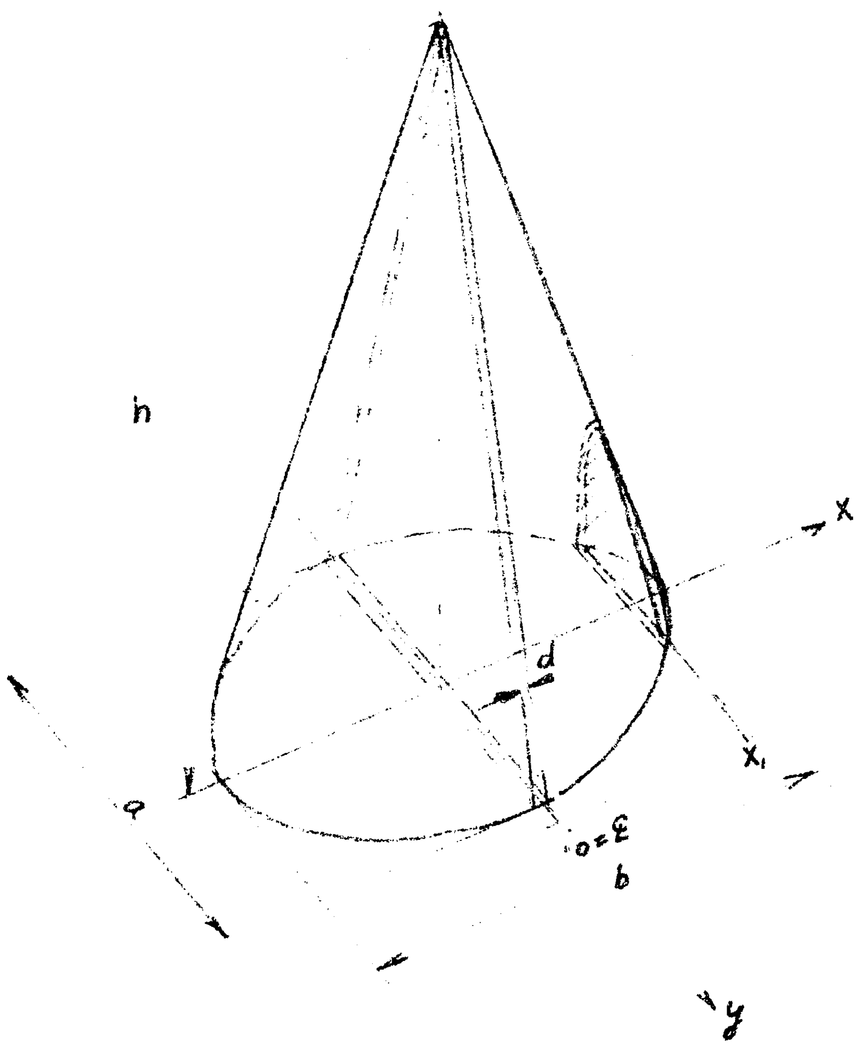
Proton Density



Aproximate Proton Density intersected by a wire ($d = 0.05$ mm) at $X = X_0$ and at any position X_1

FIG. I. 1

H. Z.

BEAM MONITOR FOR POSITION, PROFILE AND INTENSITY WITH PLATINUM WIRE

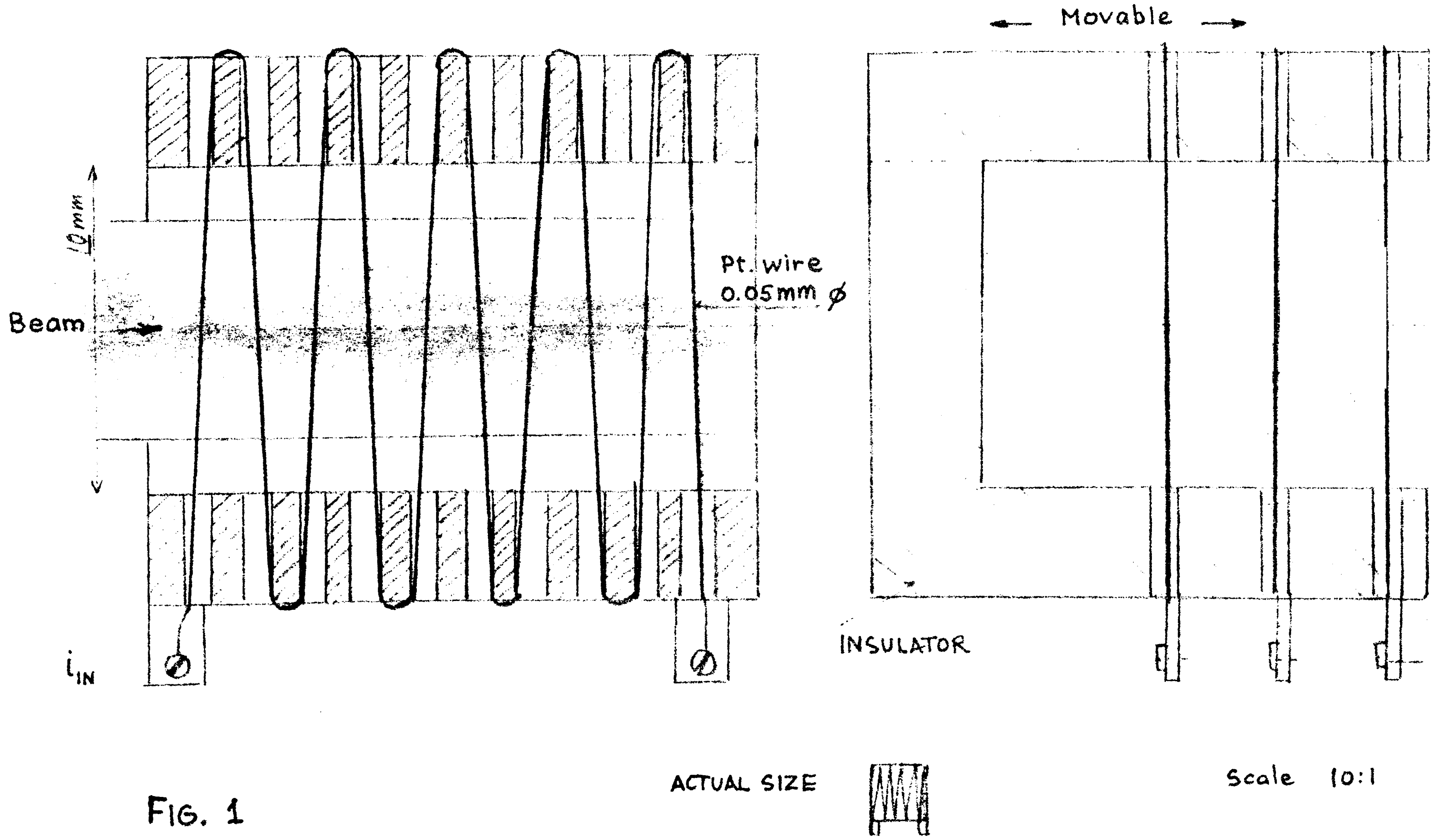


FIG. 1

H.Z.

BEAM MONITOR FOR POSITION, PROFILE AND INTENSITY WITH THERMOCOUPLES

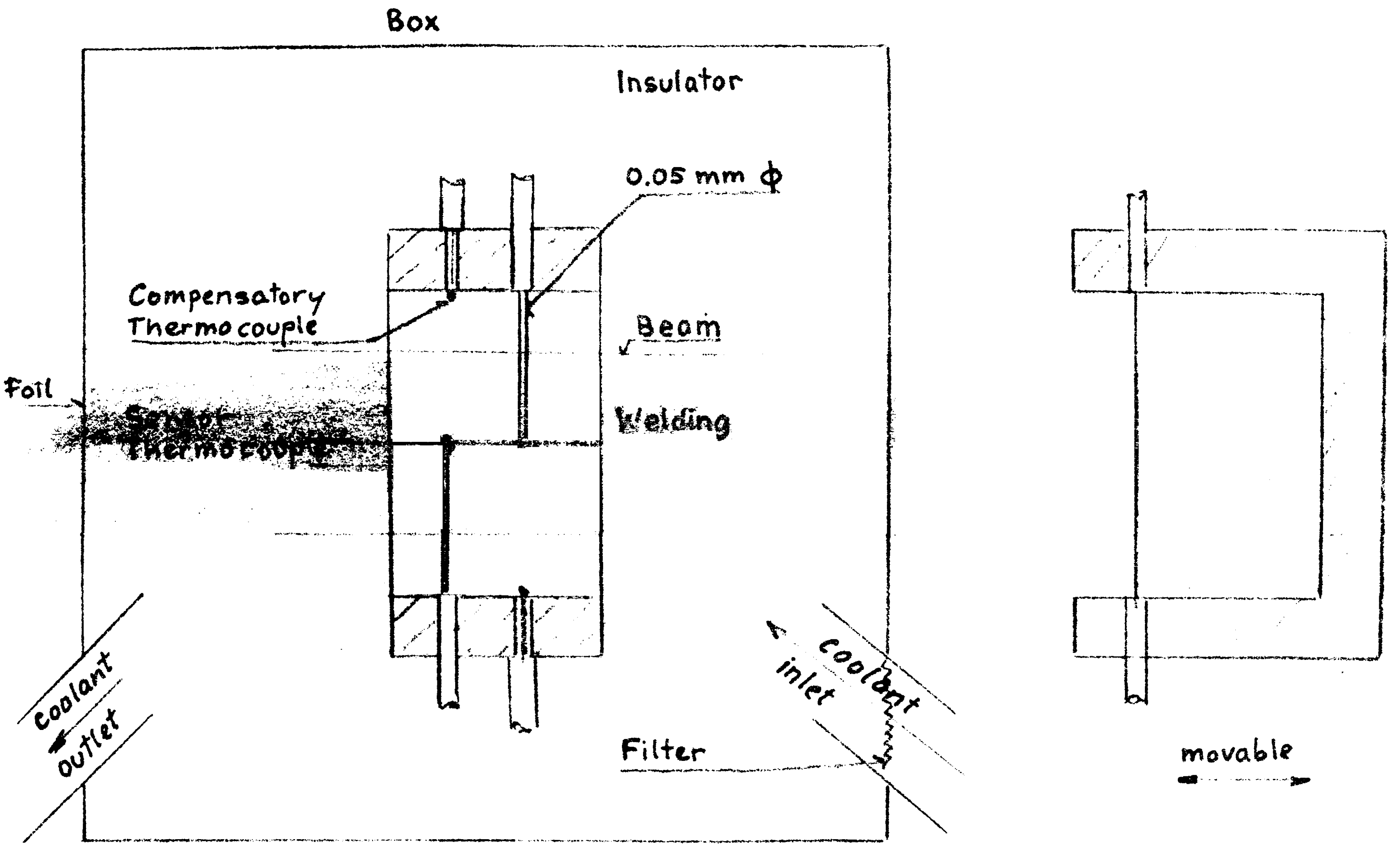
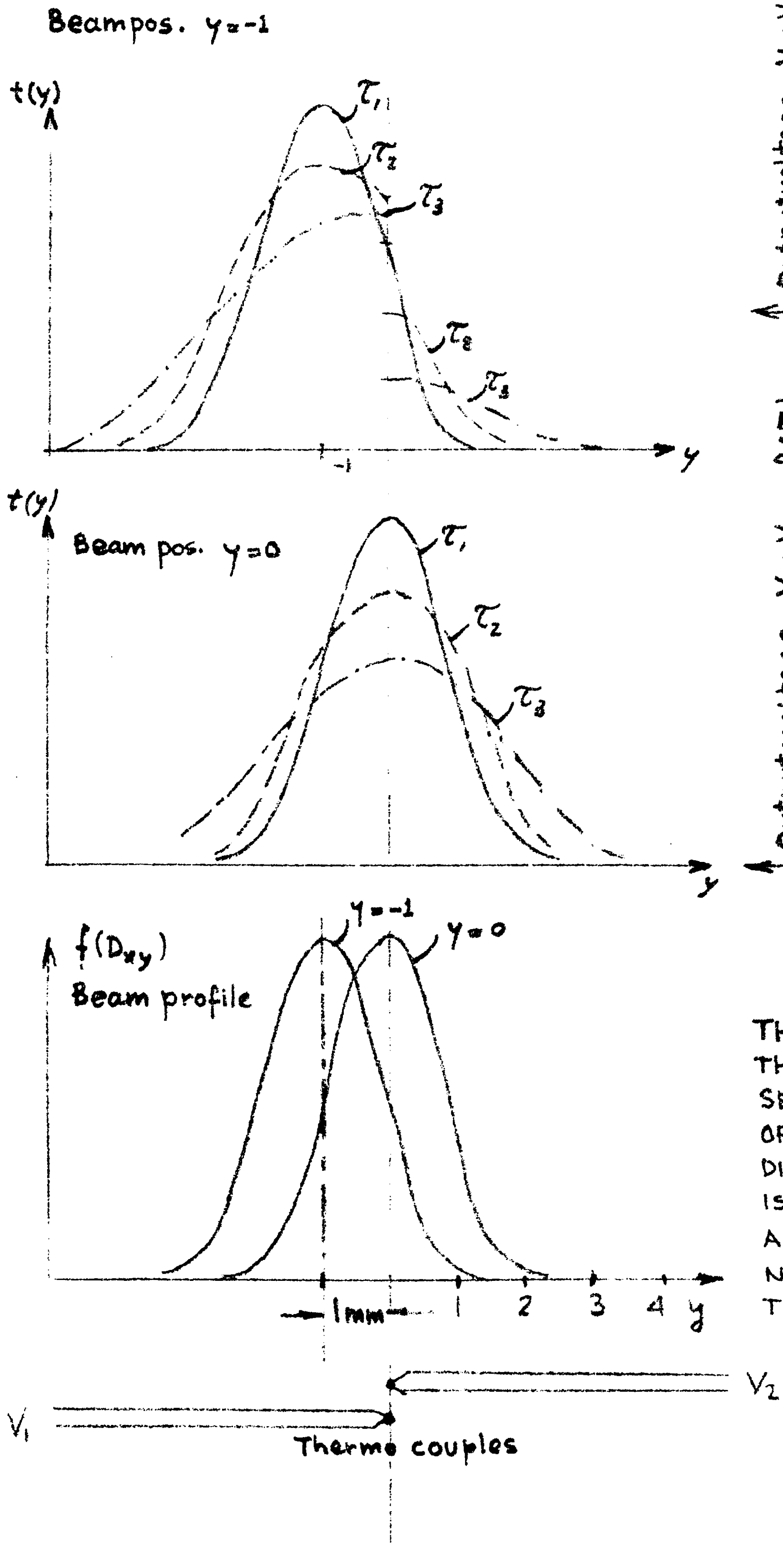


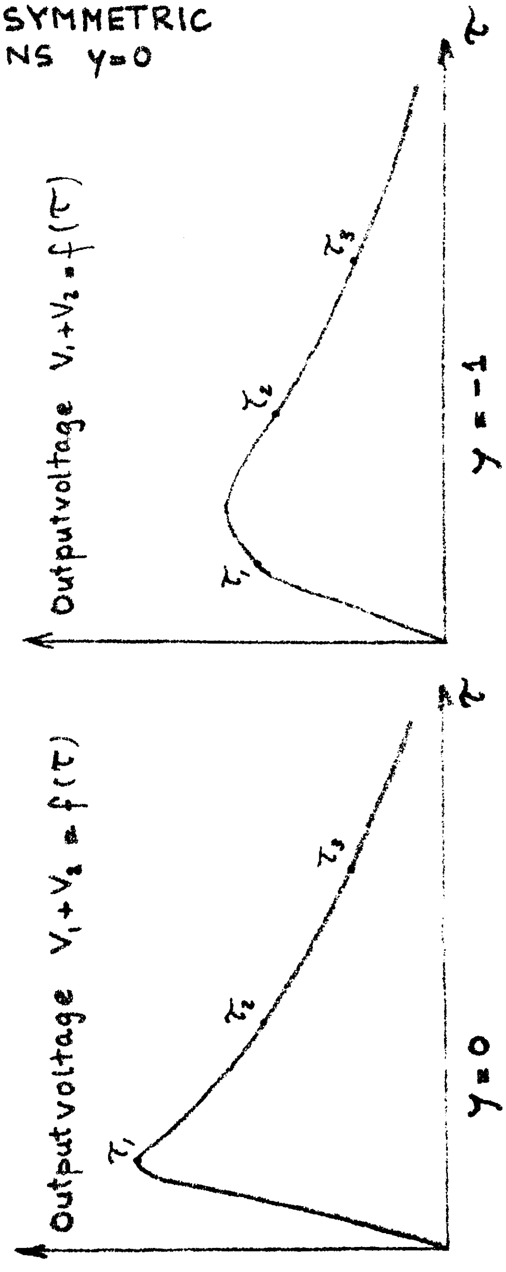
Fig. 7

Scal.: 5 1

H. Z.

ESTIMATED OUTPUT SIGNAL ON TWO SYMMETRIC THERMOCOUPLES FOR BEAM POSITIONS y=0 AND y=-1



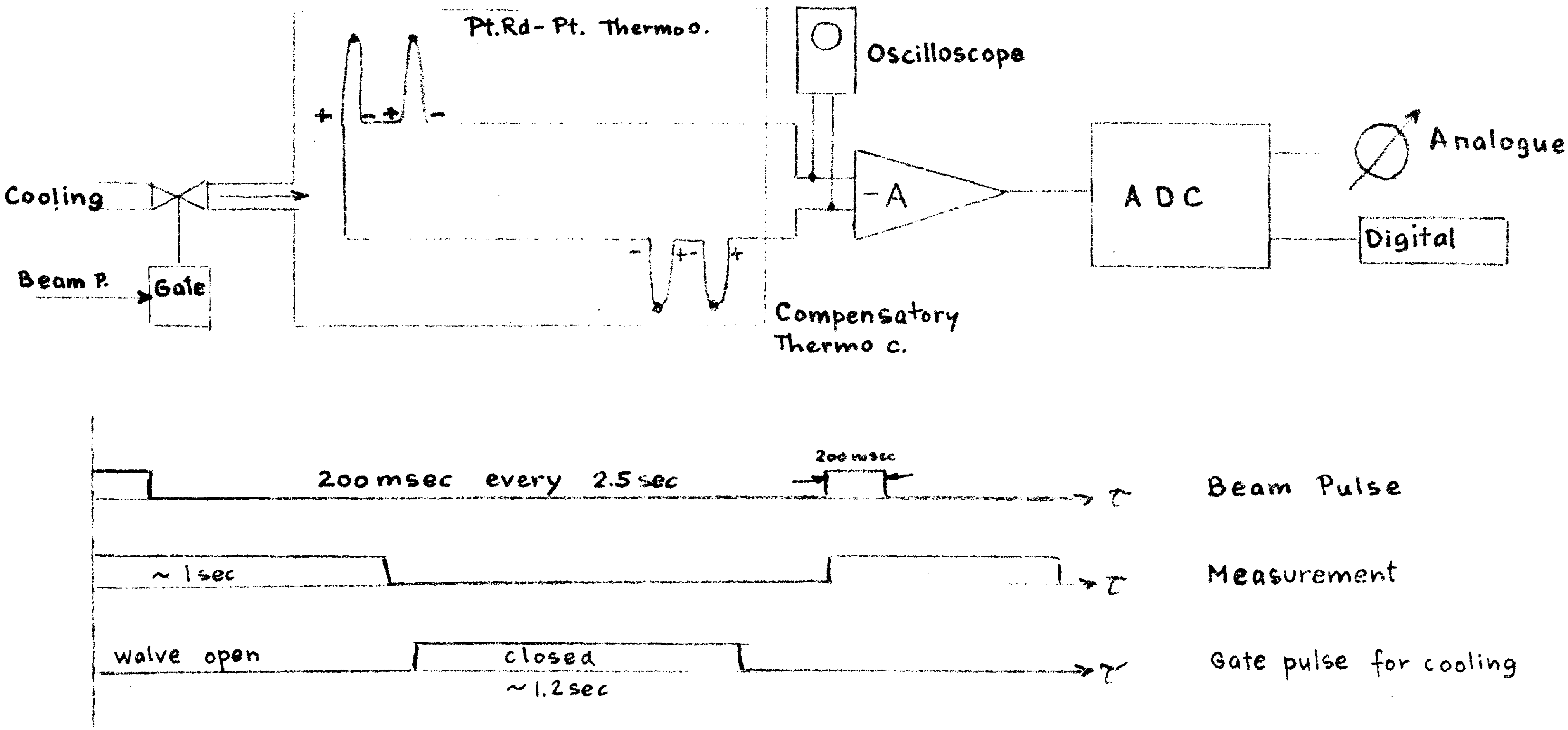


THIS ARRANGEMENT SHOWS THAT THIS BEAMMONITOR IS SENSITIVE TO A VARATION OF THE BEAM PULSE IN y-DIRECTION, IF A x-z PROFILE IS MEASURED.
A QUANTITATIVE VALUE CAN NOT BE OBTAINED FROM THESE PICTURES.

FIG. 8

H.Z.

SCHEMATIC OF THERMOCOUPLE BEAM MONITOR



Outputsignal for two Thermocouples ~ 1 mv

Accuracy : 0.1 °C relative , ±2°C absolute

FIG. 9

H.8.