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PORTABLE HIGH SENSITIVITY IONIZATION HETER

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INTRODUCTION.

When in operation the cyclotron becomes a super source of radioactivity. Since at the present stage of development it is necessary for an operator to be present at all times while the cyclotron is operating, precautions must be taken, both to shield him from and to determine the effects of the radioactive radiations. Consequently a means of measuring the radiations must be had, such a device being direct reading and portable, since field measurements of the radiation in the vicinity of the cyclotron are desirable.

The shielding of the cyclotron at M. I. T. with water barriers has been so effective that existing instruments for measuring the radiation were practically useless, because of their very low sensitivity. Dr. Livingston was therefore desirous of getting greater sensitivity out of the existing ionization meter (if possible) with the requirements that the instrument be simple, lightweight, dependable, and foolproof. As the existing instrument was decidedly too small to lend itself readily to experimentation it was decided to build an entirely new instrument.

CIRCUIT CONSIDERATIONS

The principle of the ionization meter is elementary. Ionization is produced in a confined volume (a hollow Al cylinder in this case). The ionization is collected by a charged brass rod concentric with the cylinder, and causes a current to flow through a high resistance. The voltage
drop across the high resistance is measured by a vacuum tube voltager. A simple mathematical solution can be worked out for the general case, but when resistances of the order of \(3 \times 10^9\) ohms are used, as in the present instrument, other effects which are not taken into account for the simple solution become more important.

The simple mathematical solution is as follows: For space charge limited current between plane parallel electrodes, the solution of Poisson's equation becomes,

\[ i = \alpha E^\beta \]

where,  
\( i \) = electron current  
\( E \) = potential difference between electrodes  
\( \alpha \) = constant function of geometry  
\( \beta = 3/2 \)

This equation is the familiar 3/2 power law, and shows that the current is proportional to potential difference, but the device does not function like a simple resistance.

Consider now a three element tube, the subscripts, \( p \) and \( g \) being used to denote plate and grid characteristics, respectively. The following relations will be used,

\[ \mu = \frac{\partial E_p}{\partial E_g}, \quad g_p = \frac{\partial i_p}{\partial E_p} = \frac{1}{Z_p} \]

where,  
\( \mu \) = amplification factor  
\( g_p \) = plate conductance  
\( Z_p \) = plate impedance.

Combining the two relations above gives,
\[
\frac{\partial i_p}{\partial E_j} = \mu \frac{\partial i_p}{\partial E_p},
\]

\[
g_m = \frac{\partial i_r}{\partial E_j} = \mu g_p,
\]

where \( g_m \) = mutual (grid-plate) conductance, which shall be referred to as \( g_{em} \), or effective mutual conductance.

Referring to fig. 1 we have replaced the ionization chamber by a voltage source \( e \).

![Fig. 1](image)

The analysis of fig. 1 is as follows,

\[
E_g = e_c - i_j r + i r
\]

Differentiating,

\[
\frac{\partial E_g}{\partial i} = r - r \left( \frac{\partial i_j}{\partial i} \right) \left( \frac{\partial E_g}{\partial E_j} \right)
\]

" = \( r - r \left( \frac{\partial i_j}{\partial E_j} \right) \left( \frac{\partial E_g}{\partial i} \right) \)

" = \( r - r \left( g_j \right) \left( \frac{\partial E_g}{\partial i} \right) \)

" = \( r \left( \frac{1}{1 + r g_j} \right) \)

If a current measuring device is put into the plate circuit, and has a sensitivity of \( n \) divisions per unit current, the voltage sensitivity of the circuit is,
$$S_v = \frac{\partial n}{\partial E_g} = \left( \frac{\partial i_p}{\partial E_g} \right) \left( \frac{\partial n}{\partial i_p} \right) = g_{em} S_p$$

$$S_p = \text{sensitivity of the plate current meter}$$

In terms of current,

$$S_i = \frac{\partial n}{\partial i} = \left( \frac{\partial n}{\partial E_g} \right) \left( \frac{\partial E_g}{\partial i} \right)$$

$$u = g_{em} S_p \left( \frac{r}{1 + r g_g} \right)$$

$$S_i = \text{current sensitivity of the circuit.}$$

Thus we have the sensitivity of the circuit in terms of tube parameters, but it must be remembered that the solution was arrived at neglecting complicating factors. The following is a list of some of the complicating factors:

1. Leakage over insulation (also polarization)
2. Gaseous ions
3. Thermionic emission from grid
4. Metallic ions from filament
5. Photo-electrons from grid due to light from filament
6. " " " " " soft Xrays from plate
7. Poor or improper shielding
8. Johnson or Thermal effect (in resistor)
9. Shot effect (in tube)

In the present problem the question of insulation leakage is of paramount importance, particularly in the grid circuit. Referring to Fig. 11 it will be noticed that a Victron bushing is used to connect the collector to the vacuum tube and also to
serve as moisture-proof connection. The choice of Victron was accidental, but extremely fortunate. While the leakage distances are short, the performance of the bushing is admirable. Victron appears to be fully as good as amber, which was used in the original model. The second model constructed made use of both steatite buttons and a steatite bushing (Millen). Both of these insulators have longer leakage distances, but were not so successful. The second model was built electrically identical to the first, but was almost a complete failure.

Leakage was also reduced by the choice of the tube. While the RCA 959 is intended primarily for use at higher frequencies it is well suited for this work, since the leads are placed well apart and have only glass as insulation. This may also explain, partially at least, why the Microtubes were not a success. The lead spacing is extremely small in the M54 and M74, and a metallic getter is used in addition.

Since the resistors used in the grid circuit have values as high as $3 \times 10^{11}$ ohms, grid current is important. All of the factors (2 to 9) have varying effects on the grid current. The production of gaseous ions is reduced by using reduced voltage on the electrodes of the tube. Thermionic emission from the grid is reduced both by reducing filament temperature and distance of the grid from the filament. Metallic ions from the filament can also be reduced by reducing the filament temperature. Metallic ions can also be suppressed by shielding the grid from the filament (Fig. 13).

The photo-electric current is likewise reduced by
either a reduction in the filament temperature or an increase in the filament-grid distance. X-ray photo-electric emission can be reduced by reducing the plate voltage, but X-ray emission has been observed at potentials below 3 volts.

The thermal and short effects are fundamental to the circuit. Their analytical expressions have been worked out, and they are of significance only in that they determine the limits below which a tube is useless. For the thermal effect that limit is about $3 \times 10^{-5}$ volts, and is $7 \times 10^{-5}$ volts for the short effect.

The question of poor or improper shielding will come up under the heading CONSTRUCTION.

**CONSTRUCTION**

The most important and difficult job was the building of the ionization chambers. They were both bored internally from 6 inch lengths of Al tubing 4 inches in diameter. Shoulders were left on the ends (see Fig. 2) for the purposes of mounting and holding Al foils for $\beta$-ray measurements. The first chamber is fixed directly to the box with machine screws and has no base plate, while the cover snaps on. The second chamber has a base plate and a cover which are both secured by machine screws. The second chamber was designed to be a complete and separate unit, as can be seen by Fig. 7.

The box containing the batteries, tube, meter, etc., was made of steel and is provided with a carrying handle. The dimensions of the box are 12 x 7 x 6 inches. Two designs
were attempted, and Figs. 3 to 6 show the forms. The first unit is shown in Figs. 3 and 4, while the second unit is shown in Figs. 5 and 6.

The first unit was constructed more as an experimental job to be used in the tests described later. It had no provisions for confining the high resistances and the tube in a small box for the purpose of keeping them dry.

The second unit was designed with the view in mind of sealing the high resistances and the tube in a moistureproof container. The ionization chamber and shielding can were designed to be a separate unit (Figs. 7 and 8), removable in one piece from the box. The shield is a National B30 coil shield. The resistors, switch, tube and socket, shown in Fig. 9, all fitted snugly into the coil shield, as can be seen in Fig. 10.
The shielding action of the coil shield was certainly adequate and the whole was moistureproof, but the unit was not a success because the shield was too easily deformed.

Merely squeezing the can caused changes in readings. At first it was thought that there was some electrical short, caused by
the deformation. Various thicknesses of varnished cambric were tried, and finally the can was lined with celluloid which showed no signs of puncture anywhere.

Fig. 9

Fig. 10

The leads, switch shaft, and fitting for the drying agent were all brought out through the top of the shield can.
The only detail that needs any special mention is the bushing through which the leads were brought out. Fig. 11 shows a cross section through the bushing. It consists simply of a short length (3/4 inch) of 3/8 inch lucite rod through which 5 small holes were drilled (the drilling was tedious because of the tendency of the lucite to melt.) The leads (5 in all) were cemented with glyptal into the lucite, and the lucite was in turn cemented into the brass bushing. Flexible wire was used, of course.

I feel sure that the design of the second unit (Figs. 5 to 10) is better than that of the first, and should be followed up. The shield should preferably be made of heavier Al (1/8 inch for instance) or brass. The use of any glazed insulator should be avoided. The isolantite switches and the tube socket (Hammarlund), however, seem to give no trouble at all since the microammeter needle drifts off scale when the switch is set between points.

Finally the first model was reconstructed by putting the tube and the highest resistor (3 x 10^{11} ohms) in a small sheet copper coil shield. In order to avoid any possible complication the switch and three resistors were omitted leaving only the tube and one resistor in the shield. Fig. 11 shows the details. Shunts are provided on the meter to set the ranges. As far as has been determined the performance of this model is good.

An important detail is the method of fixing the leads to the plate and grid of the RCA 959. The plate and grid
of this tube are brought out at the extremities, and the manufacturer supplies small clips to which the leads are to be soldered, since they do not recommend soldering directly to the terminals. Using these clips however made the instrument very sensitive to mechanical shocks, and errors as much as 10% to 15% were observed due to poor contacts. The simplest and best solution seems to be to solder directly to the terminals. If small wire is used the connections may be made rapidly, thus avoiding overheating and cracking the glass seal.

The drying agent is at present calcium chloride and is contained in the brass tube screwed to the bottom of the shield. (see Figs. 11 and 12. The tube is directly behind the resistor in Fig 12)
any other details should be evident from the diagrams and pictures.

TESTS

The purpose of the first tests was to determine the voltage on the RCA 959 electrodes at which maximum performance would be obtained. The circuit was the same as that of Fig. 13 except that potentiometers were put in place of the batteries in order to vary the voltages.

![Circuit Diagram](image)

The procedure was only slightly involved. A radioactive source was so arranged that it could be removed from in front of the ionization chamber, but once in place it produced constant ionization in the chamber. The source was actually a luminous clock face (see Fig. 14) which apparently produced enough alpha and gamma rays to give convenient readings on
The constancy and not the absolute value of the ionization was of importance. The various electrode voltages (excepting the filament) were varied from zero to about 20 volts (see Fig. 14). For each value of each electrode voltage, the change in plate current, $\Delta I_p$, was determined when the source was brought up and put in place. (no ionization was observed through 1/8 inches of Al, hence all readings were taken through very thin Al foil - actually foil from a package of photographic film). Since the change in any electrode voltage caused a change in plate current, the meter, $I_p$, for each voltage was set to zero by means of an auxiliary bucking circuit. A number of determinations were made and later averaged to give the curves shown in Figs. 15 to 17 and it was found that on higher values of current - i.e. 40 to 50 microamperes - the uncertainty was about 2 microamperes in 50, or about 4%. Hence all readings were taken for 30 to 40 second intervals. When it was discovered that poor connections to the plate and grid of the 959 tube were the cause of the instability, the leads were soldered directly to the tube elements and the fluctuations decreased below 1%.

The sharp peak of the plate characteristic leaves something to be desired since small battery fluctuations cause relatively larger changes in the sensitivity of the instrument. This factor may account for the partial loss in sensitivity of the instrument over a period of a few months. Other factors may be the aging of the tube and resistors.
Fig. 16
The inverse square measurements were more difficult to make. They are the results of a number of tests made over a period of time. Only one run per scale (or range) per day was made since I was warned not to expose myself more than 20 minutes a day to the source used (120 to 150 mg. Ra and products). The results are shown in figures 18, 19, and 20. (the curves marked "scale #1" and "scale #2" of Fig. 18 are evidently reversed.) In Fig. 17 the "Scale #1" curve (marked "Scale #2") for which R in Fig. 13 is equal to $9.7 \times 10^9$ ohms, shows an excellent inverse square characteristic. Why the "Scale #3" curve is better than the "Scale #2" curve (marked "Scale #1") is unknown, except that possibly when measurements were made on "Scale #2" the instrument was not allowed to warm up sufficiently. The singular behavior of "Scale #4," shown in Fig. 19 is as yet unknown. The value of R is $3.17 \times 10^7$ ohms and a number of effects (nonlinear in character) might come in as was seen under grid current discussion. The effect might also be due to a drift in warming up since this drift was always in a direction to depress the plate current but the average of a number of runs should have ironed out this effect. All curves in Fig. 18 were made using $\frac{1}{8}$ inch sheets of lead between the source and the ionization chamber.

The results of changing the plate voltage are shown in Fig. 20. These curves were run on the original model which had been remodelled. "Scale #4" on the original model is approximately equivalent to "Scale #3" on the new model.
Fig. 18

Fig. 19
**Fig. 20**

**Fig. 11**
All voltages in these tests were measured by means of a Rider "Voltohmist" which has an input resistance of 11 megohms, and hence could be put directly to the tube elements (except the suppressor) without disturbing the circuit.

The collector voltage characteristic was determined only for "Scale #4" of the new model. An a.c. power pack was used first, since measurements were made up to 400 volts, but it was so unstable that "B" batteries were the simplest solution. These tests had to be made rather carefully since relatively large surges were experienced due to charging currents when the collector voltage was changed. The curve reproduced in Fig. 21 is for "Scale #4 only of the new model, and shows that the collector voltage of the present model (62 volts) is adequate. Tests should be run on all other scales, but
Throughout all these tests attention has been focussed on "Scale #4" since it is the one most used at present in the cyclotron laboratory in detecting the presence of a beam. I anticipate that, on the other scales for the same current range ($I_p$), the voltage scale will be compressed.

The effect of resistance $R$, on the time of response of the circuit is shown in Fig. 22. The log of $R$ is plotted since the change in $R$ for the 4 scales is over 30 to 1. The words "Constant Ionization" are rather misleading, but signify that for each point, made up of several observations, constant ionization was had in the chamber. The relative position of the points was determined by allowing the plate current to drop to zero from some predetermined value, the same for all 4 scales, so that the ionization in the chamber was different.
for each point on the graph. The time of response increases very rapidly above 10" ohms. A change by a factor of 10 in the resistance, i.e. a change of one unit in logR, would make the response time go practically to infinity.

The curve of Fig. 22 certainly defines one type of response time. It would be practically impossible to plot a response curve for which the ionization for all points is the same, since full scale reading on "Scale #4" is practically imperceptible on "Scale #1."

The characteristics depicted in Figs. 23 and 24 were determined more in desperation than anything else. When I found that the Microtubes, chosen because of their low filament drain, were not so effective as the RCA 959, the question naturally was, "Why?" These curves however did not answer the question. For example, Fig. 17 shows that the maximum sensitivity, expressed as the change in plate current, $\frac{\Delta I_p}{\Delta V_g}$, per unit change in grid volts, $\Delta V_g$, of the 959 occurs at -6.5 to -7 volts, whereas Fig. 24 would indicate maximum sensitivity somewhere between -3.5 and 0 volts. For the M74 it was found that the maximum sensitivity came in the region of -5 to -6 volts, and clearly the curve of Fig. 23 indicates a maximum sensitivity between 0 and -1 volts. From these results it is evident that tube manual characteristics, determined from curves like Figs. 23 and 24, are not much help in building d.c. amplifiers using such high value resistors.
**Screen Characteristic**

Microtube M74

- $E_p = 75$ Volts
- $E_s = 15$ Volts
- $E_t = 15$ Volts
- $I_t = 24$ Mills

\[ g_s = \frac{1}{\frac{1}{g_p} + \frac{1}{E_s/E_p}} \]

**Fig. 23**

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**Suppressor Characteristic**

RCA 957

- $E_t = 15$ Volts
- $E_p = 3$ Volts
- $E_s = 15$ Volts
- $E_t = 0$ Volts

\[ g_s = \frac{-\frac{1}{g_p}}{1 + \frac{E_s}{E_p}} \]

**Fig. 24**
TWO STAGE AMPLIFIER

Having pushed the one stage job as far as possible, it might be desirable to build a two stage job to give even greater sensitivity. Consequently a two stage feedback amplifier was attempted. It was patterned after one built by Shepard Roberts (see Bibliog.) but used microtubes. Roberts' circuit is reproduced in Fig. 25. The choice of tubes was unfortunate, and coupled with the poor insulation of the steatite bushings, contributed to the failure of the experiment.

Fig. 25

The values of R in Fig. 25 are given by Roberts as follows:

(1) 10,000 mgs
(2) 2,000 mgs
The sensitivity is given by him as 10⁻¹² amps full scale (200 micreamperes). I satisfied myself that Roberts' circuit would work by building one to his specifications using a 6N5 in place of the 6K5. This amplifier was never applied to the ionization chamber, however.

My suggestion for tubes to be tried in the future is as follows:

(1) 1N5G and 1H5G
(2) 959 and 957
(3) 959 and 959 (triode)

There are other combinations, of course.

SENSITIVITY

Unless the high resistances are protected from moisture the sensitivity of the instrument is decidedly a function of the humidity. In fact the instrument refuses to function at all if the humidity becomes moderately high. Under such circumstances I found that the only way to get any results was to work with a 500 watt sun bowl playing directly on the apparatus. It was therefore deemed urgent to get the proper
components into a moistureproof container. The unit has been described elsewhere (Fig. 11), and Fig. 26 represents the electrical circuit with \( R = 3.17 \times 10^7 \) ohms. The added complexity of more resistors and a selector switch was omitted.

![Diagram](image)

**Fig. 26**

In this form the instrument was calibrated to an accuracy of 10% as there is approximately a 10% uncertainty in the strength of the source which was powerful enough to be useful. The calibration was in terms of a "safe daily dose". Thus,

- Neutron safe daily dose = 0.01\( r/\text{hr} \).
- Gamma ray " " = 0.1\( r/\text{hr} \).

\( (r = \text{roentgens}) \)

Now,

1 gram Ra @ 100 cm = 0.8\( r/\text{hr} \).
Therefore,

\[
0.1 \text{ r/h} = 150 \text{ mg of Ra @ 100 cm.}
\]

\[
0.01 \text{ r/h} = 15 \text{ " " " " " " " }
\]

The calibration of the original model (remodelled) is at present,

\[
10 \text{ ua} = 0.1 \text{ r/h.} \quad \pm 10\%
\]

and for the new model,

\[
8 \text{ ua} = 0.01 \text{ r/h.} \quad \pm 10\%
\]

\[
70 \text{ ua} = 0.1 \text{ r/h.} \quad \pm 10\%
\]

The new model is provided at present with a shunt on the meter which changes the scale by a factor of nearly 10. This shunt is not satisfactory since the single high value resistor has a response time of about 35 seconds (see Fig. 22) which means that every range will have a 35 second response time. However the more important drawback is that there is an apparent saturation at higher values of ionization. This is probably due to the excessive IR drop across the high resistor which probably drives the grid of the tube positive, whereupon it loses control of the plate current.

By returning to the design shown in Figs. 5 to 10 with attention to, (1) the mechanical strength of the shield, and (2) the type of insulation used for the collector rod a truly sensitive and rugged instrument will be the result.

Calculations based on Fig. 24, using the present bias of -6 volts show that the current sensitivity of the instrument should be about \(10^{-11}\) amps per microampere on the plate current meter, \(I_p\). The actual sensitivity is probably much less than
the above figure.

Maximum sensitivity, as determined from the curves, is had when the electrode voltages are as shown in Fig. 13. The filament battery as shown in Fig. 12 is a Burgess "4FH," next to the right are three 5540 C" batteries which supply plate and screen potentials, and the 45-volt battery, last on the right, is a Burgess "Z30N."

The electrical part of the instrument is probably as sensitive as it can possibly be made (except by using resistors higher than $3 \times 10^{11} \text{ ohms}$, but refer to discussion of Fig. 22). by the use of various gases in the ionization chamber, or by lining the walls of the chamber with certain materials, Dr. Livingston hopes to increase the sensitivity to, let us say, neutrons. His calculations show, for instance, that the collision cross-section for neutrons is greatest in nitrogen. With this in mind the second unit was originally designed so that it could be made airtight.
ACKNOWLEDGMENT

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BIBLIOGRAPHY

The literature on d.c. amplifiers was of no small assistance to me, but none of the more rugged, less specialized circuits, using ordinary commercial tubes, used resistors with as high a value as those with which I was working. The highest value resistor used anywhere seemed to be $10^{10}$ ohms while I was using resistors of $3 \times 10^7$ ohms. Most of the articles dealt with special low grid current, low leakage current tubes of special design not suited to this work. However the reader may be interested in some of the material.

(1) G.P. Harnwell and Van Voorhis-R.S.I., 5, 244, (1934)

Description with equations of a circuit of the Dubridge type applied to the FP 54 and the W.E. D06475
electron tubes. Sensitivities are also given. Design given of balanced (not a bridge) two tube circuit using type '57 tubes.

(2) D.B. Penick - R.S.I., 6, 115, (1935)

Fundamental circuits using special electrometer tubes (i.e. W.E. D96475), tube characteristics, sensitivity, stability and other curves given. Also complete procedure for balancing circuit of Dubridge and Brown type.

(3) Dubridge and Brown - R.S.I., 4, 532, (1933)

New circuit design for greater stability is given. Method of balancing out shifts due to change in filament emission.

(4) A.W. Hull - Physics, 2, 409, (1932)

Good summary of electronic tubes and devices up to 1932. Gives many references, discusses insulation, polarization, leakage, and ionization of gases in vacuum tubes.

(5) L.R. Hafstadt - P.R., 44, 201, (1933)

Use of the FP 54 in nuclear disintegration studies.

(6) Metcalf and Thomson - P.R., 36, 1430, (1930)

Description of FP 54 electrometer tube with reasons for special design.

(following three references describe the development of a specific amplifier design due to A.W. Vance.)
(7) A.W. Vance - R.S.I., 7, 489, (1936)

Description of feedback amplifier using three 184's with a sensitivity of $10^{-3}$ amps read on a 0.1 volt, 1000 ohm meter.

(8) J.M. Brumbough and A.W. Vance - Electronics, 11, Sept 16, (1938)

Further developments of Vance amplifier.

Sensitivity given as 0.00022 ua per milliamp output.

(9) Shepard Roberts - R.S.I., 10, 181, (1939)

Two stage amplifier using feedback. Reported sensitivity is $10^{-6}$ amps for full scale reading on 200 ua output meter.