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LOW ENERGY HIGH PERVEANCE ELECTRON GUN

by

G. BRESSANIN and G. HODAPP

1966

Joint Nuclear Research Center
Ispra Establishment - Italy

Physical Chemistry

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Diameter of the beam	1 mm²
Current density of the beam	.2 mA/cm²

The device consists of a Pierce-type gun and a decelerating and focusing structure. The plane electrodes were calculated with the paraxial ray equation. A description of the techniques employed for the construction has been given.

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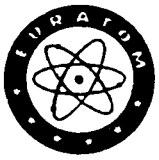

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SUMMARY

A low energy electron gun with good focusing properties has been developed. The gun can work in the following conditions :

Energy of the electrons at the target	80 eV
Diameter of the beam	1 mm^2
Current density of the beam	.2 mA/cm^2

The device consists of a Pierce-type gun and a decelerating and focusing structure. The plane electrodes were calculated with the paraxial ray equation. A description of the techniques employed for the construction has been given.

Contents

1. Introduction (*)

The research program on the electrical properties of corrosion formed ZrO_2 includes measurements of the resistance of the oxide film with conventional and with special methods. A part of the measurements program has been reported elsewhere (1); this paper deals with the less conventional part of the program and describes some of the equipment used to perform the measurements.

The report contains a description of the design of a low energy electron gun with fairly high perveance and good focusing, and of the techniques employed for its construction.

A detailed description of each step has been given with the aim of supplying informations on the difficulties encountered and on some of the possible solutions.

Manuscript received on October 26, 1966

2. Purpose of the apparatus

The principle of the measurement is the following: an electron beam scans two zirconium specimens, which are held at the same potential and are also in a symmetrical geometrical position relative to the electron gun. On of the specimens is oxidized, while the other is a reference and not oxidized. It can be shown that if the voltage of the reference sample is varied until the current on both samples is equal and if the contact potential (versus the vacuum) is known, the electrical resistance of the oxide film can be deduced from the voltage difference between the reference sample and the oxidized one.

The surface of the target is scanned by the electron beam, which is electrostatically deflected on a rectangular array of different spots on the sample. For each spot the resistance is evaluated according to the above rules and the resistance profil of the oxide film is obtained. The device is schematically shown in Fig. 1.

The same measurements will be made also, using an ion gun in the same conditions to test the influence of injected positive charge carriers on the resistivity of the oxide.

The following equipment is needed for the measurement:

a) an electron or an ion gun,

b) a power supply for the electrostatic focusing fields,

c) an electronic device to supply the necessary deflecting voltages to the gun,

d) a control system to equate the current to the reference and to the measured sample by changing the voltage applied to the first,

e) a system capable of measuring and of recording the voltage difference between the two samples, that is, to record the resistance profile of the specimen tested.

This report deals with the first part of point a), the equipment used for the control of the voltage d) is described in another paper (2), the equipment listed under c) and e) will be reported elsewhere.

3. Choice of the gun

3.1. The cathode.

Two possible solutions were investigated, namely to use flat oxide coated cathodes, directly or indirectly heated, or to use a tungsten filament cathode.

The advantages of the former solution were:

- precise geometric definition of the emitting surface and more uniform distribution of the properties of the emitted electrons,
- simplified mechanical assembly of the gun.

There were, however, some drawbacks which can be resumed as follows:

- inherent difficulty of preparation and activation of the oxide coated cathode,
- poisoning of the emitting layer by gases during operation, or by air when the gun is opened to change the Zr targets.

The tungsten filament, on the contrary, is extremely insensitive to gases during operation and can be exposed to air indefinitely without any harm. The only big disadvantage is that it is practically impossible to form the tungsten wire in such a way as to create a sufficiently large equipotential emitting surface. This would be possible only by using a thin tungsten sheet instead of a wire and by indirectly heating it (e.g. with electron bombardment) if too large currents and too large and inpractical current feed throughs are to be avoided.

Furthermore, since the working temperature of this type of filament lies above 2000°C, difficult problems would arise in the construction of the nearby electrostatic focusing electrodes.

The first solution was then preferred and preliminary tests were run to acquire a working knowledge of oxide coated cathodes, to test them with respect to all parameters concerning preparation, behaviour during operation and sensibility against poisoning when exposed to air. This work is reported in detail in section 5.1.

3.2. The electrostatic focusing system.

One of the most suitable methods to obtain a rectilinear electron flow in an electron gun with the cathode operating in space charge limited conditions is the one which is based on the exact solutions of the space charge equations for electrons leaving a space-charge limited cathode.

The focusing structure resulting from these calculations has been thoroughly studied by Pierce in the general case and is the most apt to fulfill the requirements of this particular work.

The system of electron beam and zirconium target can be compared to a diode working in space charge or in saturated conditions. The exit aperture of the gun must thus act as a victual cathode, supplying the current necessary to the diode for the given geometric conditions and applied voltages. Therefore it would be highly desirable to have

the maximum electron beam current compatible with a relatively simple design of the electrode structure. Furthermore the focusing had to be performed preferably with electrostatic fields only.

The system which was developed consists of a Pierce gun, which extracts the electrons from the cathode and shapes the beam in a well bounded cylindrical form. The further focusing and deceleration to the final low electron energy of approximately 100 eV is carried out by a set of plane parallel electrodes which slow down the electrons, thus maintaining the beam well focused and bounded.

The final deflection is performed by 2 sets of deflection plates, very similar to those used in oscillographic tubes.

The electron gun assembly is shown in Fig. 2.

4. Design of the electrostatic focusing system

4.1. Pierce gun.

The first three electrodes were calculated using the approach of Pierce. It was highly desirable to obtain a well bounded rectilinear electron flow with the cathode operating in space charge limited conditions.

A rotation symmetrical geometry was chosen being this the most satisfactory approach to the desired performances.

Pierce (3) showed that a rectilinear electron flow can be obtained, if the electrostatic field outside the beam is calculated in accordance with the boundary conditions on the interface beam-electron free space. For a rectilinear flow in space charge limited conditions, assuming also a cylindrical symmetry of the electron beam, one can make following analysis. Basing on Fig. 3 a cylindrical coordinate system is chosen z, r, φ. Numerical dimensionless coordinates are then defined yielding:

$$\zeta = \frac{z}{d} \quad \varsigma = \frac{r}{d} \tag{4.1.1.}$$

The potential is also defined as a dimensionless quantity:

$$\psi = \frac{\varphi}{\varphi_0} \tag{4.1.2}$$

where $$\varphi_0 = \left(\frac{9\,j}{4\varepsilon\sqrt{2\frac{e}{m}}} \right)^{2/3} \qquad (4.1.3)$$

$j = \frac{I}{\pi d^2}$ current density at the cathode

ε = dielectric constant in vacuum

e = charge of an electron

m = mass of an electron

As Pierce has shown in the case of bounded rectangular rectilinear flow, the potential along the z-axis must satisfy the relation:

$$\psi = \xi^{\frac{4}{3}} \qquad (4.1.4)$$

In the field free space the Laplace equation must be solved:

$$\frac{\delta^2\psi}{\delta\xi^2} + \frac{\delta^2\psi}{\delta\varrho^2} + \frac{1}{\varrho}\,\frac{\delta\psi}{\delta\varrho} = 0 \qquad (4.1.5)$$

with the following conditions at the boundary between electron beam and the field-free space:

$$\psi = \xi^{4/3}$$
$$\frac{\partial\psi}{\partial\varrho} = 0 \qquad \text{for } \xi \geq 0 \quad \varrho \geq 1 \qquad (4.1.6)$$

It is convenient to transform the equation in spherical coordinates (see Fig. 4)

$$R^2 = \xi^2 + \varrho^2 \qquad \vartheta = \text{arc cos}\,\frac{\xi}{R} \qquad \varphi^{*} = \varphi \qquad (4.1.7)$$

The Laplace equation takes the following form:

$$R\,\frac{\delta^2(R\psi)}{\delta R^2} + \frac{1}{\sin\vartheta}\,\frac{\delta}{\delta\vartheta}\left(\sin\vartheta\,\frac{\delta\psi}{\delta\vartheta}\right) + \frac{1}{\sin^2\vartheta}\,\frac{\delta^2\psi}{\delta\varphi^{*2}} = 0 \qquad (4.1.8)$$

Since ψ is not dependent on φ^* the last term of 4.1.8 vanishes.

The solutions will be of the form:

$$\psi(R,\vartheta) = R^k\,Y_k(\vartheta) \qquad (4.1.9)$$

Upon substitution of 4.1.9 in 4.1.8 and multiplication by R^k, one has:

$$k(k+1)\,Y_k + \frac{1}{\sin\vartheta}\,\frac{d}{d\vartheta}\left(\sin\vartheta\,\frac{dY_k}{d\vartheta}\right) = 0 \qquad (4.1.10)$$

The solution of 4.1.10, which is Legendre's differential equation of order k, can be given as follows:

$$P_k(\cos\vartheta) = \frac{1}{2\pi}\int_{-\pi}^{\pi}\left[\cos\vartheta + \sqrt{-1}\,\sin\vartheta\cos\beta\right]^k d\beta =$$

$$= \frac{\cos^k\vartheta}{2\pi}\int_{-\pi}^{\pi}\left[1 + \sqrt{-1}\,\mathrm{tg}\,\vartheta\cos\beta\right]^k d\beta \qquad (4.1.11)$$

The integrand of 4.1.11 is evaluated by means of a binomial expansion:

$$P_k(\cos\vartheta) = \frac{\cos^k\vartheta}{2\pi}\int_{-\pi}^{\pi}\sum_{n=0}^{k}(\sqrt{-1})^n\binom{k}{n}\mathrm{tg}^n\vartheta\cos^k\beta\,d\beta =$$

$$= \cos^k\vartheta\sum_{n=0}^{k}(-1)^n\,\frac{k(k-1)\cdots(k-2n+1)}{2^{2n}(n!)^2}\,\mathrm{tg}^{2n}\vartheta \qquad (4.1.12)$$

The boundary conditions

$$\left[\psi(R)\right]_{\vartheta=0} \propto R^{4/3} \qquad \left(\frac{\delta\psi(R,\vartheta)}{\delta\vartheta}\right)_{\vartheta=0} = 0$$

are satisfied by the Legendre polinomial of order 4/3, which gives:

$$\left[P_{4/3}(\cos\vartheta)\right]_{\vartheta=0} = 1 \qquad \left[\frac{dP_{4/3}(\cos\vartheta)}{d\vartheta}\right]_{\vartheta=0} = 0$$

The solution is then:

$$\psi(R,\vartheta) = R^{4/3} P_{4/3}(\cos\vartheta) \qquad (4.1.13)$$

The function $P_{4/3}(\cos\vartheta)$ vanishes for $\vartheta_o = 71^o$, this gives the shape (4.1.14) of the first equipotential surface, while the others are generated by the condition

$$R^{4/3} P_{4/3}(\cos\vartheta) = \text{constant.}$$

4.2. Decelerating and focusing field.

The gun was designed as mentioned previously on the basis of the usual accelerating-decelerating approach.

For the design of the decelerating and focusing field the following assumption was made:

- The device will be working in a vacuum of approximately 10^{-7} Torr. At this pressure the number of ions generated

by the electron beam and by impact with other ions is sufficiently high to counteract the effect of the space charge, specially for small current densities. Furthermore it would be very difficult to make a numerical guess of this parameter, which obviously depends in great extent on the working pressure in the gun. If one were to account for this, one had to change continuously the parameters (e.g. potentials) of the decelerating system as a function of the pressure in the gun. This would create quite difficult control problems and the system would be in any case dependent on the accuracy of the pressure measurements. As a consequence the first calculations were made neglecting the space charge effects and the velocity spreading due to the thermal velocities in the gun. After construction, tests have been run to check if the results are satisfactory and if the above assumptions are met.

In the coordinate system of Fig. 3, r, z, φ, in the case of symmetry around the z-axis one can write for the potential V:

$$\frac{\delta^2 V(z,r)}{\delta z^2} + \frac{1}{r} \frac{\partial V(z,r)}{\partial r} + \frac{\partial^2 V(z,r)}{\partial r^2} = o \qquad (4.2.1)$$

If one considers electron paths very close to the axis, a series expansion of V(z,r) can be performed around r = o, z

$$V(z,r) = V(z,o) + \frac{\partial V(z,o)}{\partial r} r + \ldots + \frac{\partial^n V(z,o)}{\partial r^n} \frac{r^n}{n!} + \ldots \qquad (4.2.2)$$

For symmetry reasons one can write:

$$V(z,-r) = V(z,r) \tag{4.2.3}$$

and conclude that in the series expansion all the coefficients of $r^{(2i+1)}$ with $i = 0, 1, 2, \ldots, k, \ldots$ must identically vanish:

$$\frac{\partial^{(2i+1)} V(z,o)}{\partial r^{2i+1}} = o \qquad i = o, 1, 2, \ldots, k, \ldots \tag{4.2.4}$$

Therefore 4.2.2 can be rewritten as:

$$V(z,r) = V(z,o) + \frac{\partial^2 V(z,o)}{\partial r^2} \frac{r^2}{2!} + \ldots + \frac{\partial^{2n} V(z,o)}{\partial r^{2n}} \frac{r^{2n}}{2n!} + \ldots \tag{4.2.5}$$

The second term of 4.2.1 must now be evaluated:

$$\lim_{r \to o} \frac{\partial V(z,r)}{\partial r} \cdot \frac{1}{r} \overset{H}{=} \lim_{r \to o} \frac{\partial^2 V(z,r)}{\partial r^2} = \frac{\partial^2 V(z,o)}{\partial r^2} \tag{4.2.6}$$

Upon substitution in 4.2.1 one gets for $z, r = o$:

$$\frac{\partial^2 V(z,o)}{\partial r^2} = -\frac{1}{2} \frac{\partial^2 V(z,o)}{\partial z^2} \tag{4.2.7}$$

The last expression and 4.2.5 give:

$$V(z,r) = V(z,o) - \frac{r^2}{4} \frac{\partial^2 V(z,o)}{\partial z^2} \tag{4.2.8}$$

where the higher order terms have been neglected for very small r ($r \ll 1$).

Consider now an electron of mass m and charge -e subject to the electrostatic fields of the system. The equations of motion in r and z direction are:

$$\frac{d^2r}{dt^2} = \frac{e}{m} \frac{\partial V(z,r)}{\partial r} = \eta \frac{\partial V(z,r)}{\partial r} \qquad (4.2.9)$$

$$\frac{d^2z}{dt^2} = \frac{e}{m} \frac{\partial V(z,r)}{\partial z} = \eta \frac{\partial V(z,r)}{\partial z} \qquad (4.2.10)$$

The time is now eliminated from the last two equations.

Supposing $r = r(z(t))$ the following relations hold:

$$\frac{dr}{dt} = \frac{dr}{dz} \frac{dz}{dt}$$

$$\frac{d^2r}{dt^2} = \frac{dr}{dz} \frac{d^2z}{dt^2} + \frac{d^2r}{dz^2} \left(\frac{dz}{dt}\right)^2 \qquad (4.2.11)$$

$$\frac{d}{dz} \left(\frac{dz}{dt}\right)^2 = 2 \frac{d^2z}{dt^2} = 2\eta \frac{\partial V(z,r)}{\partial z} \qquad (4.2.12)$$

Integrating 4.2.12 one gets

$$\left(\frac{dz}{dt}\right)^2 = 2\eta V(z,r) + R(r)$$

Boundary conditions are:

$$\left(\frac{dz}{dt}\right)_{z=o} = o$$

or

$$R(r) = -2\eta V(o,r)$$

The potential at the cathode is:

$$V(o,r) = o$$

Therefore one gets:

$$\left(\frac{dz}{dt}\right)^2 = 2\eta V(z,r) \qquad (4.2.13)$$

The expressions 4.2.11, 13, 9 and 10 give:

$$\frac{d^2r}{dt^2} = \eta \frac{\partial V(z,r)}{\partial r} = \frac{dr}{dz}\eta \frac{\partial V(z,r)}{\partial z} + \frac{d^2r}{dz^2} 2\eta V(z,r) \qquad (4.2.14)$$

In order to study paraxial electrons, only terms in $O(r^1)$ will be retained.

Differentiation of 4.2.8 gives in this approximation:

$$\frac{\partial V(z,r)}{\partial r} = -\frac{r}{2}\frac{\partial^2 V(z,o)}{\partial z^2} \qquad (4.2.15)$$

$$V(z,r) = V(z,o) + \frac{r\,\partial V(z,o)}{\partial r} + \frac{r^2}{2!}\frac{\partial^2 V(z,o)}{\partial r^2} + \cdots \qquad (4.2.16)$$

In this approximation and considering also the expressions 4.2.3 and 4.2.4., 4.2.16 reduces to:

$$V(z,r) = V(z,o) \tag{4.2.17}$$

$$\frac{\partial V(z,r)}{\partial z} = \frac{\partial V(z,o)}{\partial z} + r \frac{\partial^2 V(z,o)}{\partial z \partial r} + \frac{r^2}{2!} \frac{\partial^3 V(z,o)}{\partial z \partial r^2} + \cdots \tag{4.2.18}$$

An electrostatic potential must have finite second order derivatives with respect to space coordinates. On the other hand each of these derivatives must be symmetrical in r. This is possible only if

$$\frac{\partial^2 V(z,o)}{\partial z \partial r} = o \tag{4.2.19}$$

Thus in this approximation one gets:

$$\frac{\partial V(z,r)}{\partial z} = \frac{\partial V(z,o)}{\partial z} \tag{4.2.20}$$

Equation 4.2.14 becomes with 4.2.17 and 20:

$$\frac{\partial V(z,r)}{\partial r} = \frac{dr}{dz} \frac{\partial V(z,o)}{\partial z} + 2 \frac{d^2 r}{dz^2} V(z,o) \tag{4.2.21}$$

4.2.15 substituted in 4.2.21 gives the equation of motion of electrons close to the z-axis, neglecting the space charge effects:

$$\frac{\partial^2 V(z,o)}{\partial z^2} r + 2 \frac{\partial V(z,o)}{\partial z} \frac{\partial r}{\partial z} + 4 V(z,o) \frac{\partial^2 r}{\partial z^2} = o \tag{4.2.22}$$

For a given potential distribution along the z-axis, equation 4.2.22 gives the desired shape of the paraxial electron path, i.e. $r = r(z)$ for $r \ll 1$.

The opposite is also true, that is, if one prescribes a path $r = r(z)$, the distribution $V(z,o)$ is found, which is compatible with such a flow.

An appropriate shape of the electron trajectories is the following

$$r(z) = r_o e^{-\alpha z}$$

For this $r(z)$ the solution of 4.2.22, with the boundary conditions:

$$z = o \qquad V(o,o) = A$$
$$z = l \qquad V(l,o) = B$$

is:

$$V(z,o) = e^{\alpha z} \; A \left[\cos \sqrt{3}\alpha z - \sin \sqrt{3}\alpha z \left(\operatorname{cotg} \sqrt{3}\alpha l - \frac{B \; e^{-\alpha l}}{A \sin \sqrt{3}\alpha l} \right) \right] \qquad (4.2.23)$$

The tabulation of this function was carried out on the IBM 7090 digital computer for

$$A = 850 \text{ V}$$
$$B = 40 \text{ V}$$
$$\alpha = .01$$
$$l = 60 \text{ mm}$$

The result is given in Table I.

TABULATION NO. 1

THE PARAMETERS ARE

A = 8.50E 02 B = 4.00E 01 ALFA = 10.00E-03 L = 6.00E 01

DISTANCE		BEAM RADIUS		POTENTIAL	
Z(1) = 0. MM		R(1) = 2.0000 MM		V(1) = 850.00 VOLT	
Z(2) = 2.0 MM		R(2) = 1.9604 MM		V(2) = 868.00 VOLT	
Z(3) = 4.0 MM		R(3) = 1.9216 MM		V(3) = 883.93 VOLT	
Z(4) = 6.0 MM		R(4) = 1.8835 MM		V(4) = 897.69 VOLT	
Z(5) = 8.0 MM		R(5) = 1.8462 MM		V(5) = 909.15 VOLT	
Z(6) = 10.0 MM		R(6) = 1.8097 MM		V(6) = 918.21 VOLT	
Z(7) = 12.0 MM		R(7) = 1.7738 MM		V(7) = 924.75 VOLT	
Z(8) = 14.0 MM		R(8) = 1.7387 MM		V(8) = 928.66 VOLT	
Z(9) = 16.0 MM		R(9) = 1.7043 MM		V(9) = 929.83 VOLT	
Z(10) = 18.0 MM		R(10) = 1.6705 MM		V(10) = 928.14 VOLT	
Z(11) = 20.0 MM		R(11) = 1.6375 MM		V(11) = 923.48 VOLT	
Z(12) = 22.0 MM		R(12) = 1.6050 MM		V(12) = 915.73 VOLT	
Z(13) = 24.0 MM		R(13) = 1.5733 MM		V(13) = 904.79 VOLT	
Z(14) = 26.0 MM		R(14) = 1.5421 MM		V(14) = 890.53 VOLT	
Z(15) = 28.0 MM		R(15) = 1.5116 MM		V(15) = 872.85 VOLT	
Z(16) = 30.0 MM		R(16) = 1.4816 MM		V(16) = 851.64 VOLT	
Z(17) = 32.0 MM		R(17) = 1.4523 MM		V(17) = 826.79 VOLT	
Z(18) = 34.0 MM		R(18) = 1.4235 MM		V(18) = 798.18 VOLT	
Z(19) = 36.0 MM		R(19) = 1.3954 MM		V(19) = 765.72 VOLT	
Z(20) = 38.0 MM		R(20) = 1.3677 MM		V(20) = 729.30 VOLT	
Z(21) = 40.0 MM		R(21) = 1.3406 MM		V(21) = 688.81 VOLT	
Z(22) = 42.0 MM		R(22) = 1.3141 MM		V(22) = 644.15 VOLT	
Z(23) = 44.0 MM		R(23) = 1.2881 MM		V(23) = 595.24 VOLT	
Z(24) = 46.0 MM		R(24) = 1.2626 MM		V(24) = 541.97 VOLT	
Z(25) = 48.0 MM		R(25) = 1.2376 MM		V(25) = 484.26 VOLT	
Z(26) = 50.0 MM		R(26) = 1.2131 MM		V(26) = 422.01 VOLT	
Z(27) = 52.0 MM		R(27) = 1.1890 MM		V(27) = 355.14 VOLT	
Z(28) = 54.0 MM		R(28) = 1.1655 MM		V(28) = 283.58 VOLT	
Z(29) = 56.0 MM		R(29) = 1.1424 MM		V(29) = 207.25 VOLT	
Z(30) = 58.0 MM		R(30) = 1.1198 MM		V(30) = 126.08 VOLT	
Z(31) = 60.0 MM		R(31) = 1.0976 MM		V(31) = 40.00 VOLT	

5. Experimental development

5.1. The cathode.

The cathode was machined from high purity nickel with the dimensions given in Fig. 5. It was heated in a vacuum better than 10^{-6} Torr at a temperature of 1100°C to degase and to clean it. The pressure must not rise above 10^{-3} Torr during the process. The cleaning is accomplished (if the pressure remains in the range of 10^{-6} Torr) when a cathode temperature of 1000°C is reached. In this case the pressure becomes better than 10^{-7} Torr by cooling the cathode to room temperature.

It is usually recommended that controlled amounts of reducing agents be added to the nickel in order to obtain optimum performance characteristics of the cathode during activation and life (4). The nickel alloys best suited to be used as cathode sleeve metal are commercially available and are usually doped with Cu, Fe, Mu, Al and other metals. Experiments were run with the alloy L of the firm Vacuumschmelze Aktiengesellschaft, Hanau, which has the following composition:

% in weight	Mg	Si	Al	Mu	Fe	Cu	S	C	C_o
Ni L	0.04	0.15-0.25	0.01	0.22	0.1	0.03	0.005	0.1	1

The difference between cathodes made with this alloy and the ones made with pure nickel were, however, so small that only pure nickel was adopted for the cathodes of the gun.

The advantages of the alloys are especially important if good performances during the life of the cathodes are to be expected. The apparatus developed here, on the contrary, has to be exposed very often to the air and reactivated each time, so that the oxide coating must be eventually removed and substituted. As a consequence, a long cathode life is of very small importance, and pure nickel is satisfactory.

The nickel sleeve is indirectly heated by a tungsten filament, wound on an aluminium oxide form. The filament is 0.2 mm in diameter, and requires a maximum of 6A at a voltage of 6-12 V. The aluminium oxide form is made by Degussa, type MA 90, No. 51015 / 10 µm.

The coating applied to the cathode has the following composition:

Barium carbonate	($BaCO_3$)	57 %
Strontiumcarbonate	($SrCO_3$)	38 %
Caliumcarbonate	($CaCO_3$)	5 %

The carbonates were simultaneously precipitated by addition of sodium carbonate solution to the corresponding nitrates dissolved in water. After filtration and thorough washing they were dried at 105°C for 12 hours and allowed to cool down in a dry atmosphere. They were then ground in a ball mill to obtain an ultimate grain size of 1 µ.

The binder composition is given as follows:

nitrocellulose	12.2 %
ethyl alcohol	6.6 %
amyl acetate	81.2 %
total solids	12.2 %

The mixture was again ground in a ball mill for about 24 hours. The cathode was coated by painting the emitting surface with the carbonates and binder solution.

The cellulose binder was removed by baking it for 2 hours at 500°C in a vacuum better than 10^{-5} Torr.

The activation process involved two steps (4):

a) conversion of the carbonates into oxide,
b) partial reduction of the oxides at the metal-coating interface to produce free barium throughout the coating by diffusion.

The conversion takes place at a temperature between 850 and 900°C, a gas outburst can be observed at about 750°C, but the pressure after conversion should lie in the range of 10^{-6} Torr.

The cathode temperature should then be raised in the range between 1000 and 1200°C, and a D-C voltage can be applied to draw a current of about 25 ma/cm^2. The pressure should not rise above some 10^{-6} Torr during this process.

After 5 minutes the cathode temperature can be reduced in the operating range of 800°C for stabilizing the emission.

The usual emission currents which were obtained for the cathodes (25 mm^2 emitting surface) were in the range of 5 to 10 mA and were stable during the whole trial time of about 24 hours.

Experiments were run to test the efficiency of the cathode after exposure to air.

They gave the following results:

a) cathode not heated during the exposure to air.
   1 - First exposure to air during 15 minutes:
   after reactivation the emission was the same
   as before.
   2 - Second exposure: The emission decreased
   40 % of its maximum value.

b) cathode heated at 150°C during the exposure.
   1 - First exposure to air during 15 minutes:
   the cathode retained its full emission properties
   after reactivation.
   2 - Second exposure: a decrease of 30 % of the
   previous value was observed.

A third exposure to air gave emission values too small to be useful for any practical work.

The cathode assembly is shown in Fig. 6.

5.2. Pierce gun and focusing electrodes.

The three electrodes of the Pierce gun were machined from aluminium in the required shape. They were equally spaced and a large electrode diameter was chosen to prevent a deformation of the electric field caused by the edges.

The dimensions were:

outer diameter	40 mm
diameter of the aperture	4 mm
distance between the electrodes	5 mm

The focusing electrodes were made of 0,5 mm thick stainless steel sheet, all other dimensions were the same.

All electrodes were heated in vacuum at 400°C for 6 hours to degas and to clean them.

5.3. Mechanical assembly.

The electrodes were placed between 4 small quartz bars. Glass spacers were used to set the distance between adjacent electrodes and 4 springs were used to press all the electrodes together. With this construction the electron lenses were very well aligned and the whole system could be easily installed in the glass enclosure.

The eleotrodes were separately supplied with the appropriate voltage by means of current feed throughs, which also served to support the system.

The gun is shown in Fig. 7 and 8. The system was evacuated by an oil diffusion pump, with a pumping speed of 300 l/min., the ultimate vacuum was better than 10^{-7} Torr. The whole glass system was placed in an oven, where it could be conveniently heated to degas the water adsorbed on the inner walls.

6. Performances.

The tests which were performed on the device were aimed to investigate the following points:

a) diode characteristics

b) focusing of the beam

For both measurements an anode was provided, which could be moved in a plane perpendicular to the axis of the electron beam by means of an external magnet. As can be seen in Fig. 9 the current through the central electrode can be separately measured. The whole useful target area can be scanned and the focusing of the electron beam can be easily checked.

a) Diode characteristic.

The characteristic is shown in Fig. 10, where the voltages are given with respect to the cathode.

The useful working range is in the saturation region, where the internal differential resistance is about 1 μA/V. The maximum attainable current is about 80 μA at a diode voltage of 400 V, but the working current of 10 - 20 μA meets very well the required performances.

b) Focusing characteristic.

The focusing characteristics are shown in Fig. 11. The ratio between measured current and maximum current is shown as a function of the distance from the maximum point. Three curves are shown, corresponding to three different voltages, which are

measured between the anode and the last focusing electrode.

In the best case, the spot diameter, for a 1 : 10 current ratio is 1 mm, this result can be considered to be quite satisfactory and fits very well the requirements of the measurements which will be performed with the gun.

It can be now concluded that the assumptions made in section 4.2. are met within the discussed limits, and that the electron gun, up to the present, is very well apt to be used for the measurements of the electrical properties of ZrO_2.

7. Conclusions

A very well focused electron beam of low energy and fairly high current density has been designed and tested with the following results:

spot diameter for a current ratio $\frac{I}{Imax} = 0.1$	~ 1 mm^2
current density of the beam	$\sim .2$ $\frac{mA}{cm^2}$
energy of the electrons at the target	$\sim$ 80 eV

The design of the electron lenses has been performed in two steps, the first one made use of the exact solutions of the space charge equation for cylindrical rectilinear electron flow, the second one made use of the paraxial ray equation to get the shape of the focusing and decelerating fields.

The second part of the work is devoted to the construction of the gun and to the check of its performances against the required specifications.

The gun has been designed for a very special application, but its use might be extended to other fields, requiring low energy and well focused electron beams (e.g. electron diffraction studies etc.).

8. References

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3. J.R. Pierce, "Theory and Design of Electron Beams", Van Nostrand, New York, 1954.

4. W.H. Kohl, "Materials and Techniques for Electron Tubes", General Telephone & Electronic Technical Series, Reinhold Publishing Corporation, New York, N.Y., 1960.

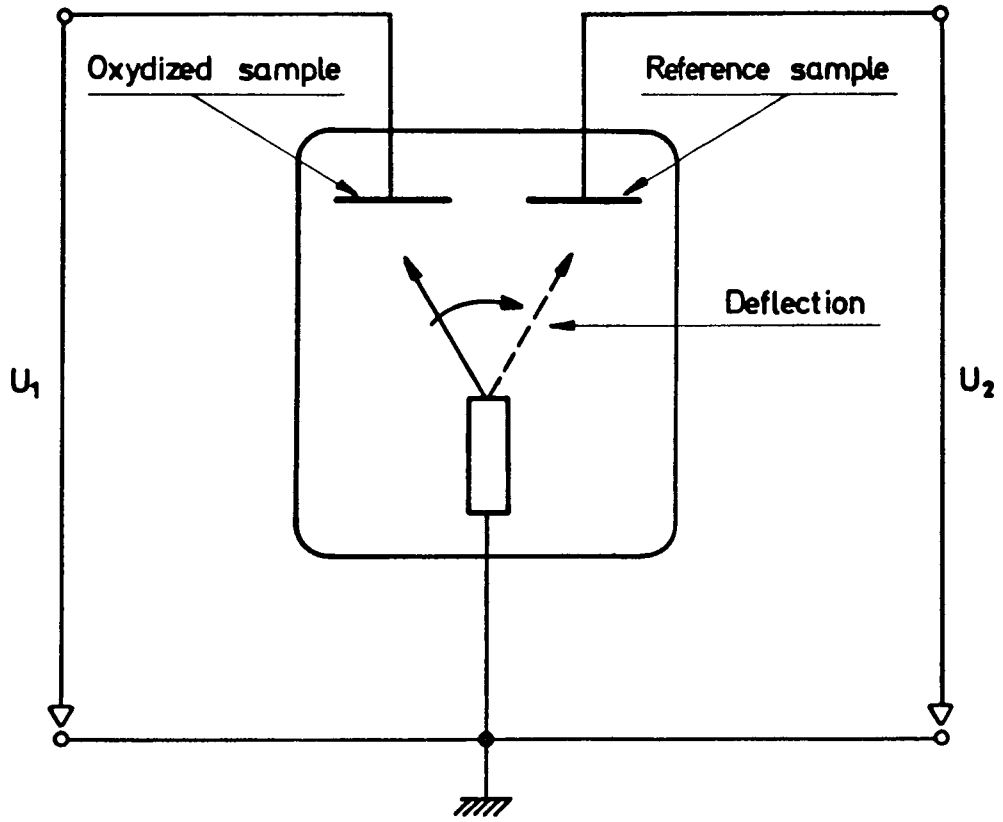

Fig. 1 ELECTRON GUN ASSEMBLY TO MEASURE THE RESISTANCE OF ZrO_2.

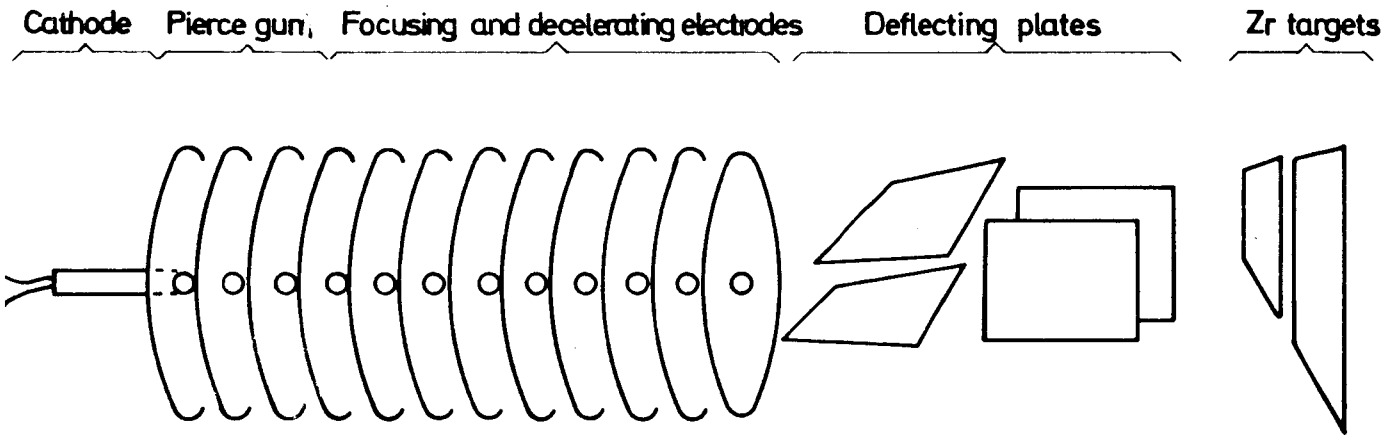

Fig. 2 ARTIST'S REPRESENTATION OF THE ELECTRON GUN.

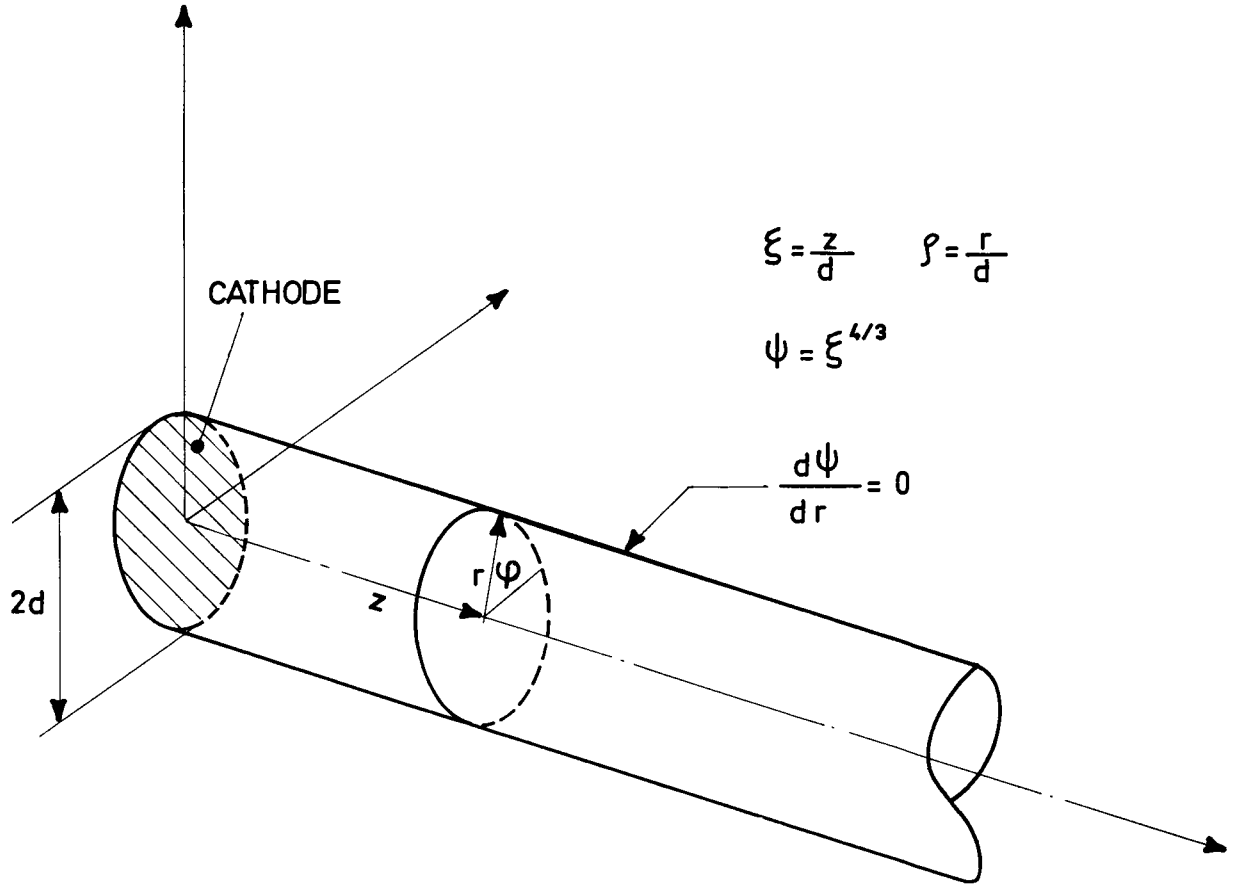

Fig. 3 CYLINDRICAL COORDINATE SYSTEM

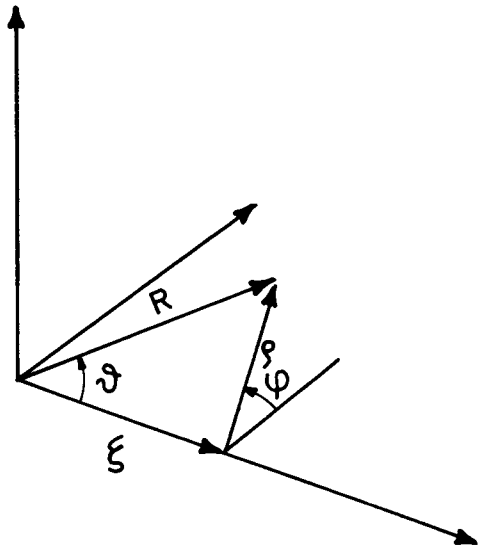

Fig. 4 SPHERICAL COORDINATE SYSTEM

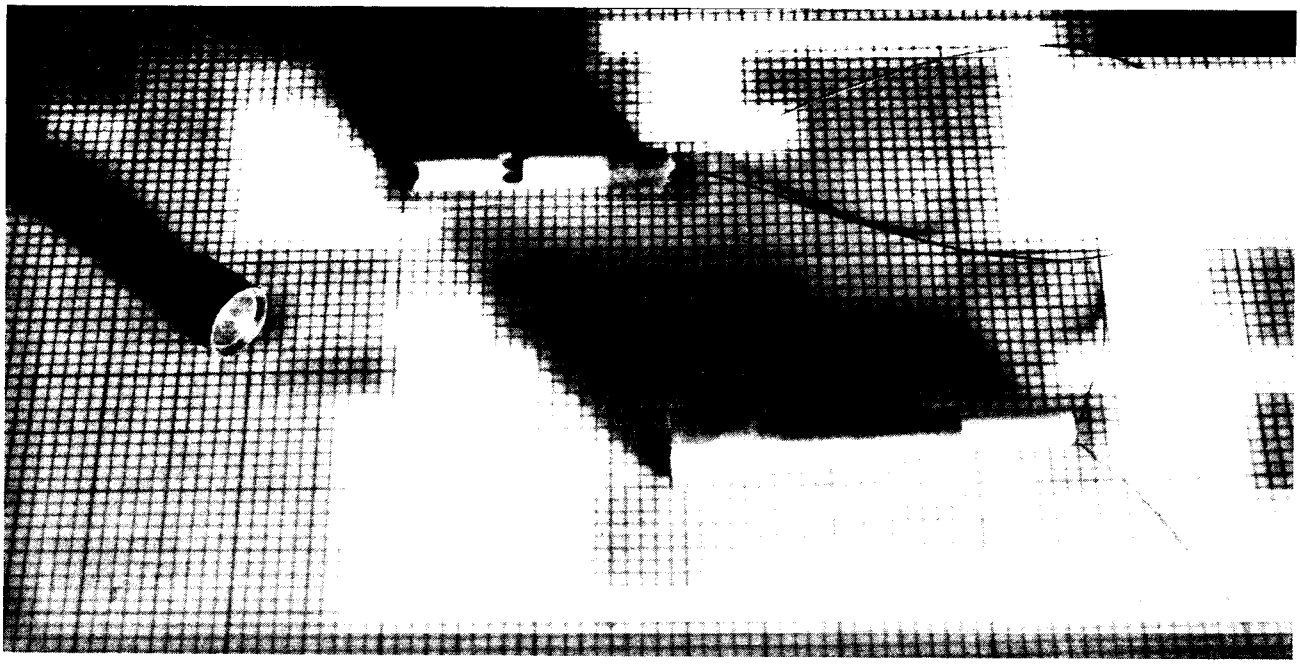

Fig. 5 The indirectly heated cathode

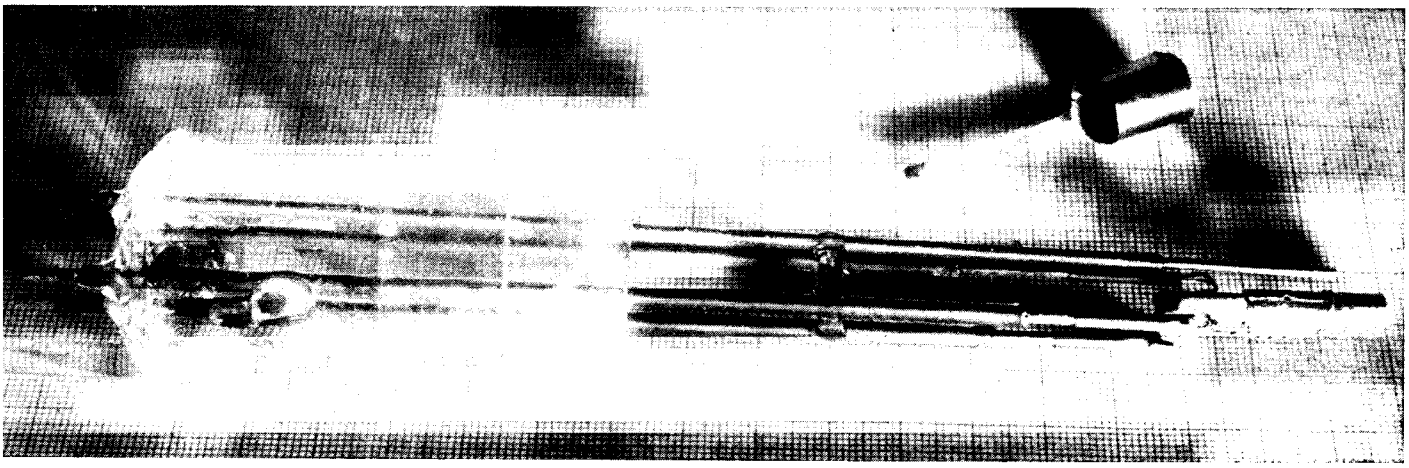

Fig. 6 Cathode assembly

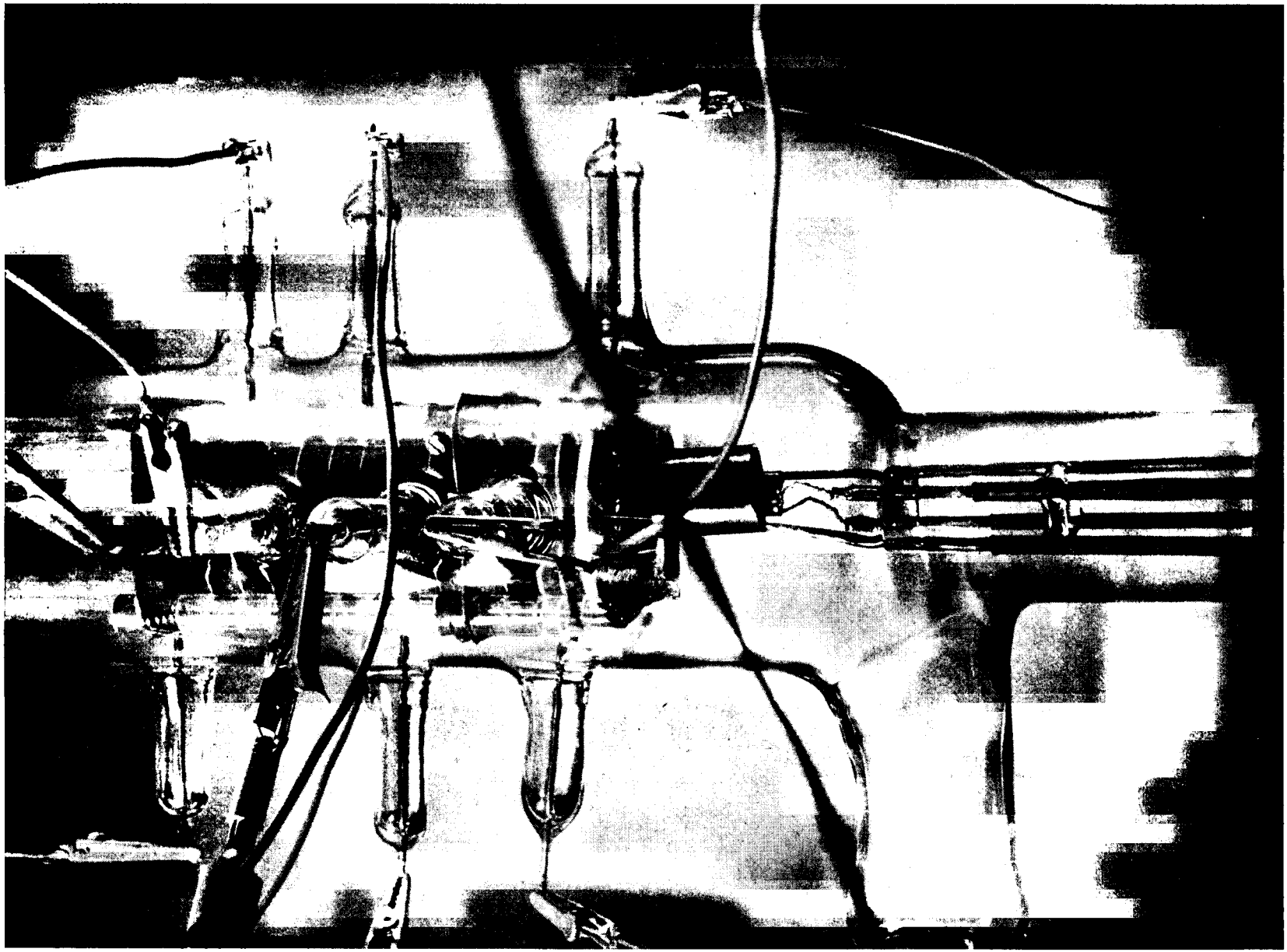

Fig. 7. Close-up view of the electron gun

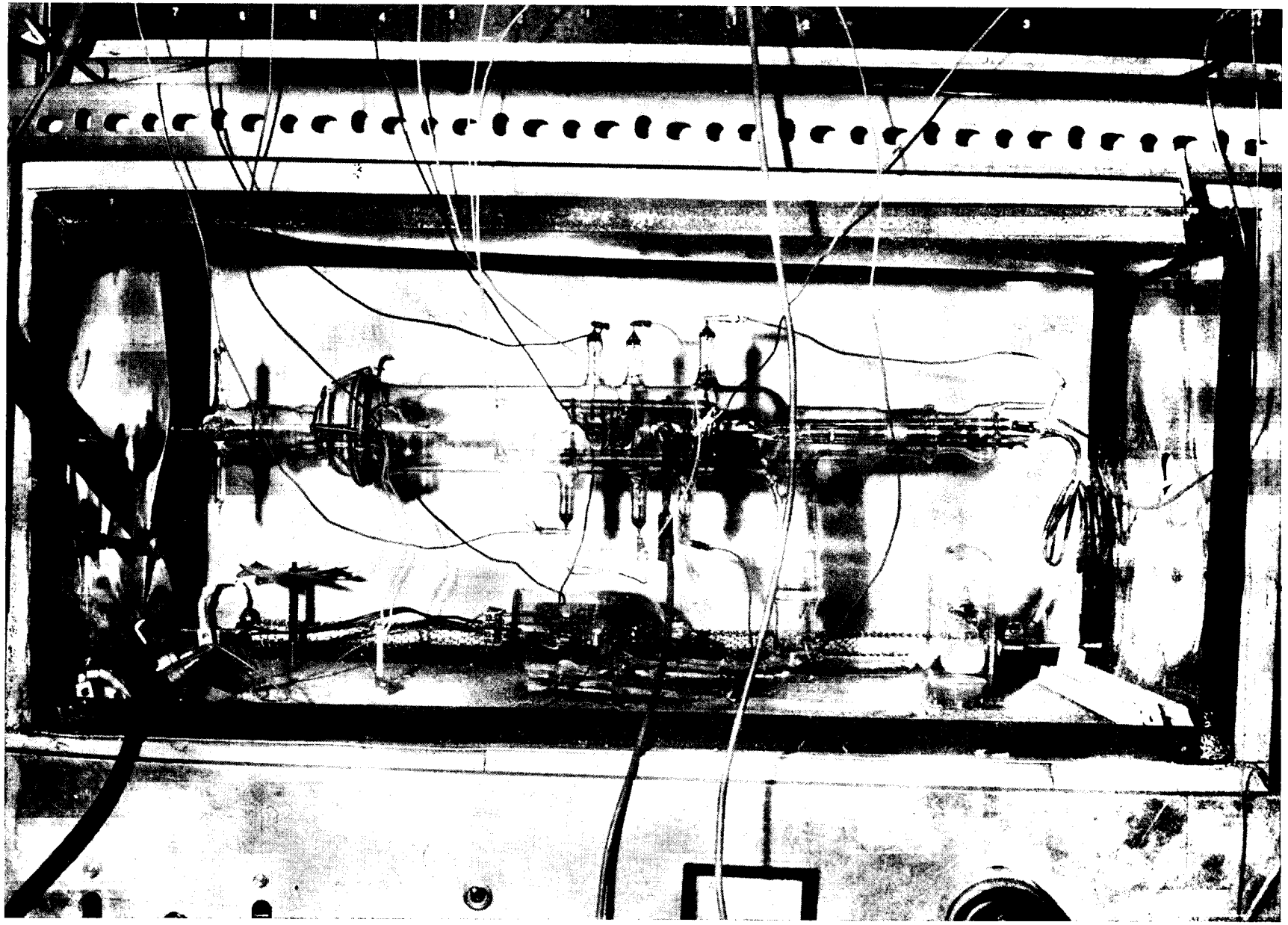

Fig. 8 General view of the electron gun in the oven

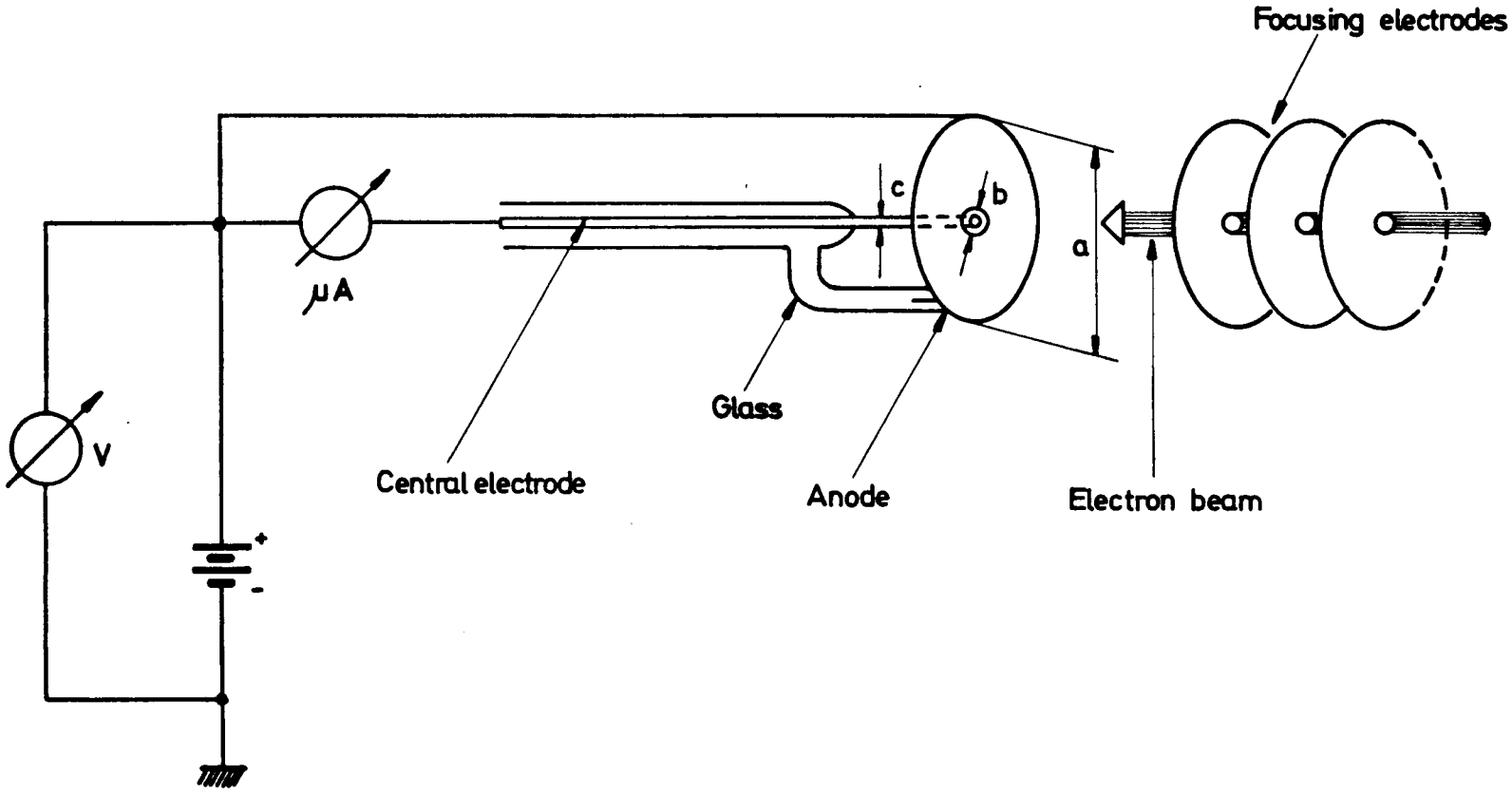

Fig. 9 ANODE ASSEMBLY (a = 40mm, b = 1.25mm, c = 1mm) AND CIRCUIT FOR THE MEASUREMENT OF THE FOCUSING PROPERTIES.

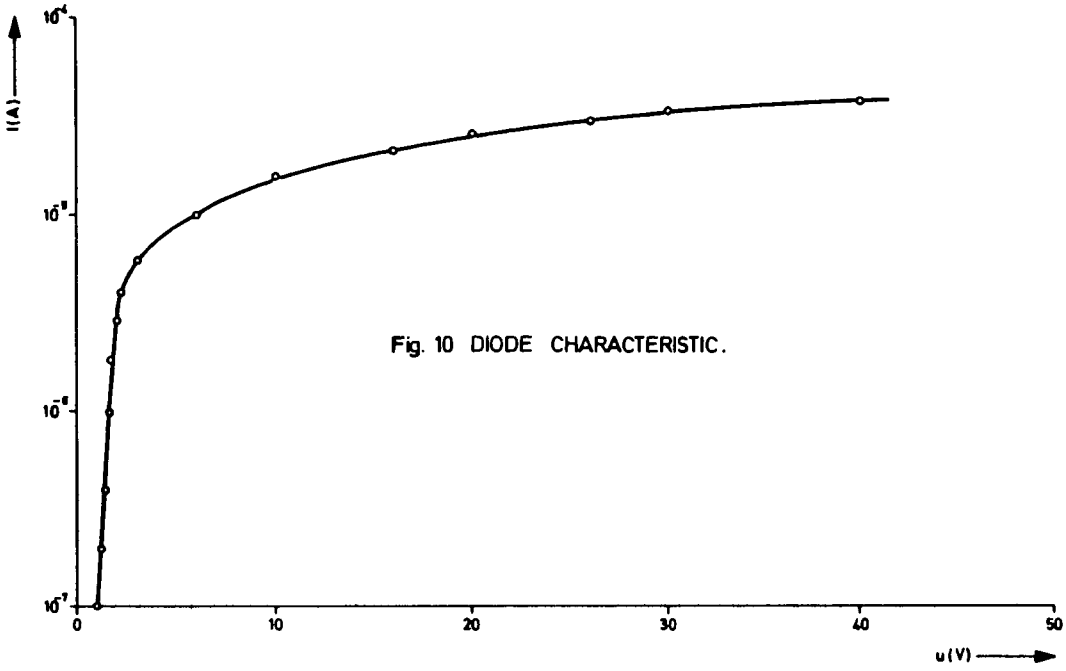

Fig. 10 DIODE CHARACTERISTIC.

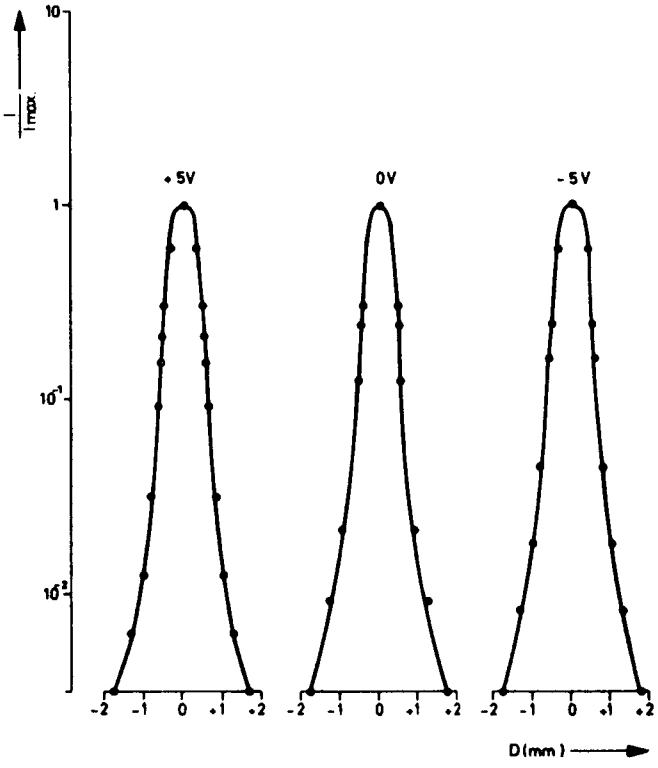

Fig. 11 FOCUSING CHARACTERISTIC.

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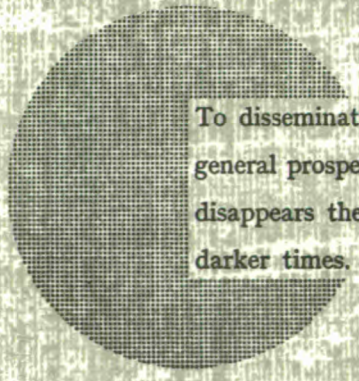

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Alfred Nobel

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