ELECTRON DIFFRACTION

According to deBroglie, particles have a wave nature with their wavelength given by $\lambda = h/p$; where p is momentum and h is planck's constant. That this is so can be demonstrated by the observation of electron diffraction. Since we will be using nonrelativistic electrons their momentum can be calculated using $p = \sqrt{2mk}$; where m is the electron rest mass and K is kinetic energy. In this experiment the electrons will be given kinetic energy by accelerating them through a measurable electric potential, i.e., K = eV. A useful equation that gives the wavelength as a function of the electric potential in is

$$\lambda = \frac{h}{\sqrt{2meV}}; \qquad (1)$$

where e is the charge of an electron and V is the electric potential.

Since this wavelength is of the order of the lattice spacing in crystals it is reasonable to expect a diffraction pattern to appear when electrons in the energy range of a few keV are scattered by a crystalline lattice.

Fig. 1 shows the reflection of two rays (electron paths) which will be coherent (in phase) if $2d\sin\theta = n\lambda$; where d is the spacing between Bragg planes (lattice spacing) and n is an integer. This is known as Bragg's law.

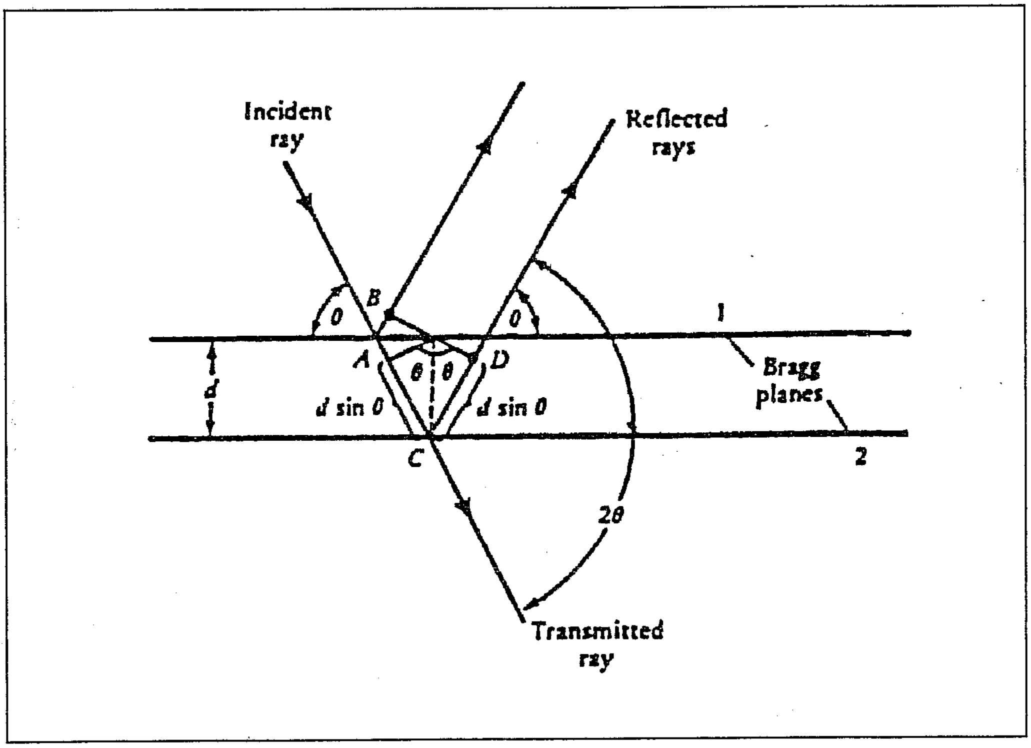


Figure 1

Figures 2a and 2b show the geometry appropriate for single-crystal and poly-crystalline electron diffraction, respectively.

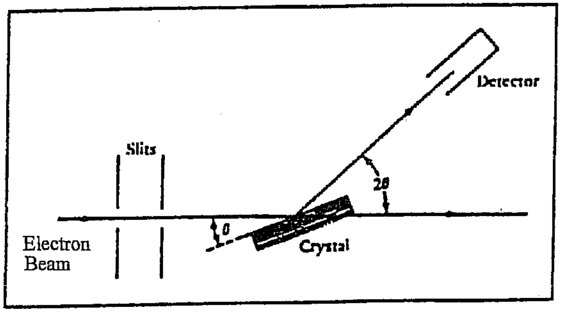


Figure 2a

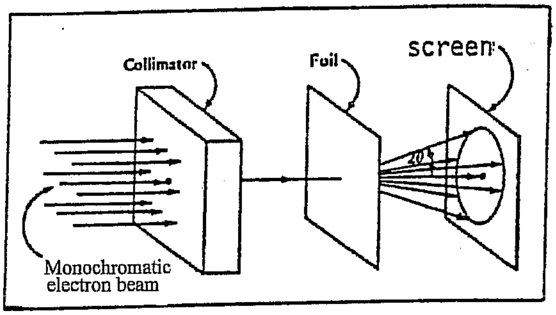


Figure 2b

Note that in either figure the angle between the incident and reflected ray, which you will measure, is $\phi = 2\theta$. Bragg's law can be rewritten as

$$n\lambda = 2d\sin\theta = 2d\sin(\phi/2) \approx 2d(\phi/2) = d\phi$$

for small angles. Also note that in the polycrystalline case (Fig. 2b), the crystals are randomly oriented and that those satisfying Bragg's law will give a circular pattern on the screen due to rotational symmetry about the azimuthal axis (beam direction).

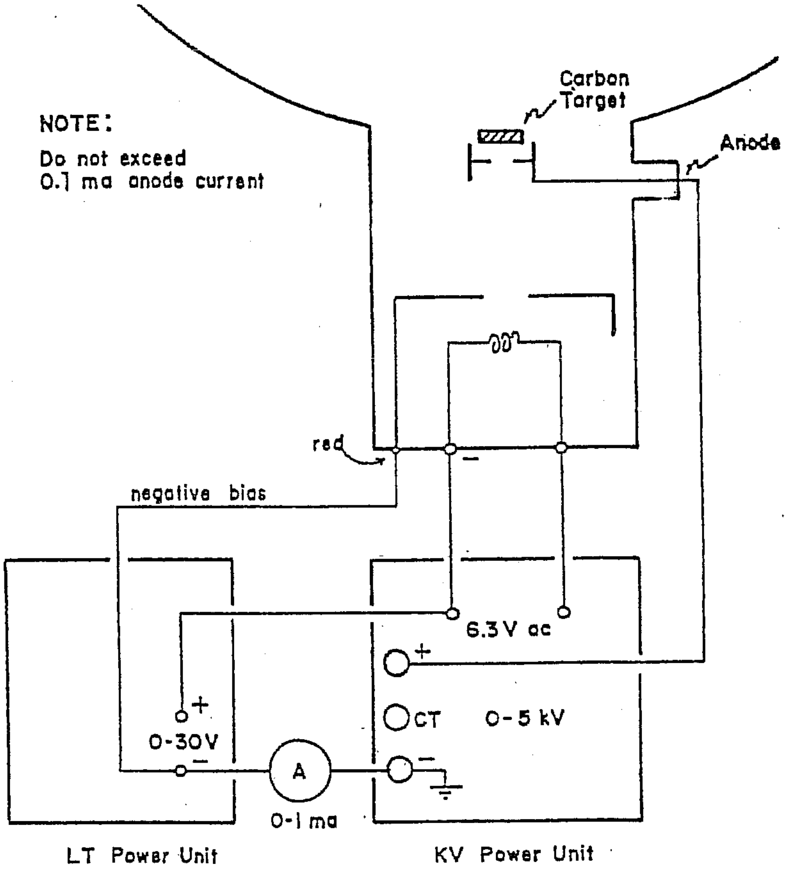
If L is the distance between the polycrystalline foil and the screen, the diameters of circular patterns will be given by $D = 2L\phi$ (See Fig. 2b). Using Bragg's law for first-order reflection (n=l), $D = 2L(\lambda/d)$ And finally, inserting our expression for λ, we get

$$d = \frac{2Lh}{D\sqrt{2meV}} \tag{2}$$

Experimental Procedure

1. The circuit for the experiment is as shown in Fig. 3. The target is carbon in the form of polycrystalline graphite foil. Graphite has a hexagonal crystal structure.

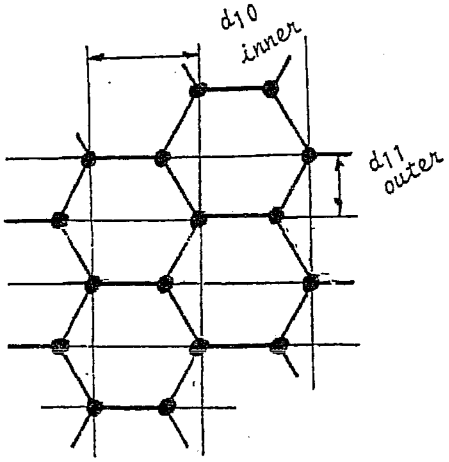
2. For various accelerating potentials, measure the diameter, D, of each of the two prominent diffraction circles observed. The best results are obtained when the beam intensity is minimum (this also prolongs the life of the tube), therefore turn up the negative bias shown in Fig. 3 to lower the current. A table similar to the one shown on page 4 can be used.



NOTE:
Do not exceed
0.1 ma anode current

"Electron Diffraction" Circuit
Fig. 3

Fig. 4



Distance to screen

L = 13.5 cm

Lattice spacings

d_{11} = 1.23 Å

d_{10} = 2.13 Å

Voltage	D (inner)	D (outer)

3. Putting equation 2 in the form $\frac{2Lh}{\sqrt{2meV}} = dD$ we see that (d) is the slope of a graph of $\frac{2Lh}{\sqrt{2meV}}$ versus. D. Perform a least squares analysis of your data and obtain the lattice spacings d_{10} and d_{11}

4. Compare (use % error) the lattice spacings you measured with the known spacings between one set of planes given in Fig. 4.

5. Calculate the ratio d_{10}/d_{11} for your measured lattice spacings and compare the value with the theoretical value of $\sqrt{3}$ for a hexagonal crystal.

Questions:

1. Were there any circular patterns other than the two prominent ones you measured? From Fig. 4 and using geometry you can find other spacings which might predict other rings. When you do, make sure that the adjacent planes contain the same number of atoms per unit area. Some of the rings may be too weak to see because of the smaller number of atoms per unit area.

2. Fig. 4 emphasizes the spacing between planes of atoms in a mosaic of hexagons. Consider the third dimension, the altitude of the hexagonal crystals. How would the circular patterns produced by planes in this dimension with spacings larger than d_{11} compare with the pattern associated with the smaller spacing?

3. Why does a polycrystalline target produce circles?

4. What pattern would you see expect if the target were a single crystal, i.e. a pure crystal, rather than a polycrystalline crystal?

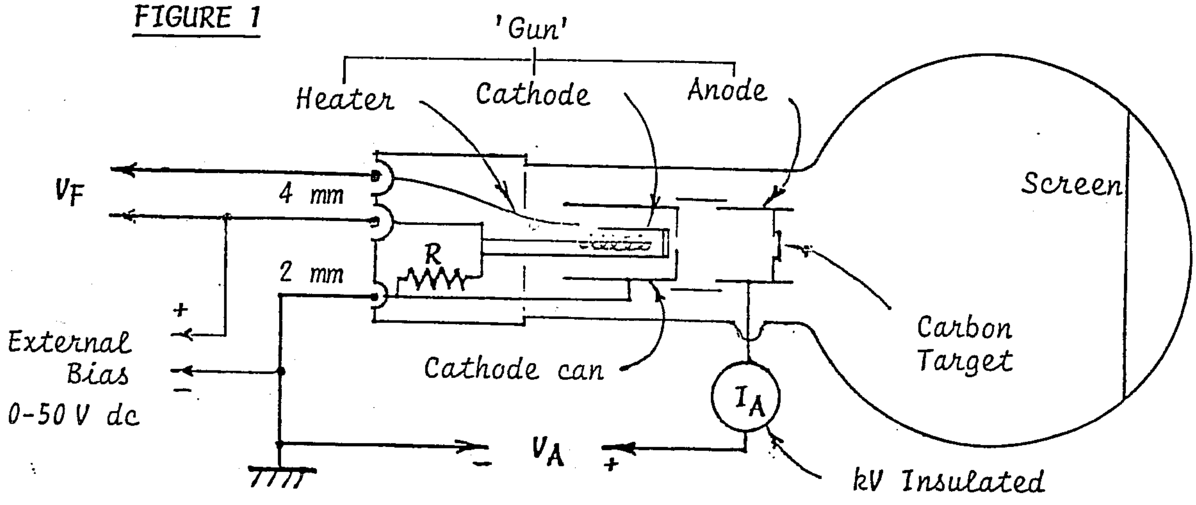
THE ELECTRON DIFFRACTION TUBE, TEL.555, comprises a 'gun' which emits a narrow converging beam of electrons within an evacuated clear glass bulb on the surface of which is deposited a luminescent screen. Across the exit aperture of the 'gun' lies a micro-mesh nickel grid onto which has been vapourised a thin layer of graphitised carbon; the beam penetrates through this carbon 'target' to become diffracted into two rings corresponding to separations of the carbon atoms of 0.123 and 0.213 nanometers. The source of the beam of electrons is an indirectly-heated oxide-coated cathode, the heater of which is connected to 4mm sockets in a plastic cap at the end of the neck; a 2mm plug is supplied with each tube for connecting the negative line of the E.H.T supply to the can surrounding the cathode via a 2mm socket in the base-cap; this socket is internally connected to the negative heater socket by a resistor, R , to achieve 'negative auto-bias' of the cathode-can. The E.H.T positive potential is applied to the anode of the 'gun' through a 4mm plug mounted on the side of the neck.

The tube can be mounted on the Universal Stand, TEL.501.

Specification:

FILAMENT VOLTAGE	(V_F)	...	6.3 V ac/dc (8.0 V max.)
ANODE VOLTAGE	(V_A)	...	2500 - 5000 V dc
ANODE CURRENT	(I_A)	...	0.15 mA at 4000 V (0.20 mA max.)

FIGURE 1



Protection of the Carbon Target.

The graphitised carbon through which the electron beam is confined to pass is only a few molecular layers in thickness and can be punctured by current overload.

The purpose of 'negative auto-bias' is to reduce the likelihood of damage to the target due to accidental user-abuse. The total emitted current passes through the resistor R ; increase in the current causes the cathode-can to become more negatively biassed, so reducing the emitted current.

CONNECT THE E.H.T NEGATIVE TO THE 2MM SOCKET ONLY.

Practical precautions.

Current overload causes the target to become overheated and to glow dull-red; it is good practise to inspect the target periodically during an experiment and especially at switch-on when at least one minute should be allowed for the cathode temperature to stabilise before applying anode voltage.

As an additional safeguard, the anode current should be metered and never allowed to exceed 0.2 mA; higher anode voltages can be achieved without exceeding this limit by reducing the heater voltage (see page 6, NOTE 2).

CONNECT THE E.H.T NEGATIVE TO THE 2MM SOCKET ONLY.

External biassing.

The focus of the beam of electrons may be varied by the degree of bias of the cathode-can; improved focussing sharpens the diffraction pattern for better observation at lower E.H.T settings (see page 6, NOTE 2).

External control can be achieved by connecting the negative heater socket and the 2mm socket (and thus the cathode-can) to a 0-50 V variable source; negligible current is required and the beam can be 'cut-off' at about -40 Volts.

CONNECT THE E.H.T NEGATIVE TO THE 2MM SOCKET ONLY.

Recommended Experiments:

Experiments with the Maltese Cross Tube, TEL.523, demonstrate that cathode rays exhibit some properties that seem similar to those of light and other properties that appear to be consistent with those of electrically charged particles. It was suggested by **Louis de Broglie** in 1926 that particles could have wave properties where the wavelength, λ , is inversely proportional to momentum, M ($= mv$).

The Teltron Series 'A' Experiments confirm that electrons obey the laws of motion and lead to a measure of the specific charge e/m . The Millikan experiment establishes the discrete nature of the electron, gives a measure of charge e and thereby an evaluation of its mass m . Sufficient information is thus available to test the de Broglie hypothesis.

The possibility of diffraction:

A calculation using de Broglie's equation shows that electrons accelerated through a p.d. of 4 kV have a wavelength of about 0.02 nanometers. Interference and diffraction effects, as studied in physical optics, demonstrate the existence of waves, where for a simple ruled grating, the condition for diffraction is $\lambda = d \sin \theta$, where d is the spacing of the grating and where for small angles $\sin \theta = \theta$.

The best man-made gratings are ruled at 2,000 lines per mm and with a wavelength of 0.02 nm , the angle θ will be less than one second of arc or only 0.5 mm at 10 m from the grating. If electron diffraction is to be observed in a Teltron tube with a pathlength of 140 mm, the spacing between 'rulings' to produce a first order of interference at 14 mm from zero (i.e $\sin \theta = 0.1$), must be 0.2 nm.

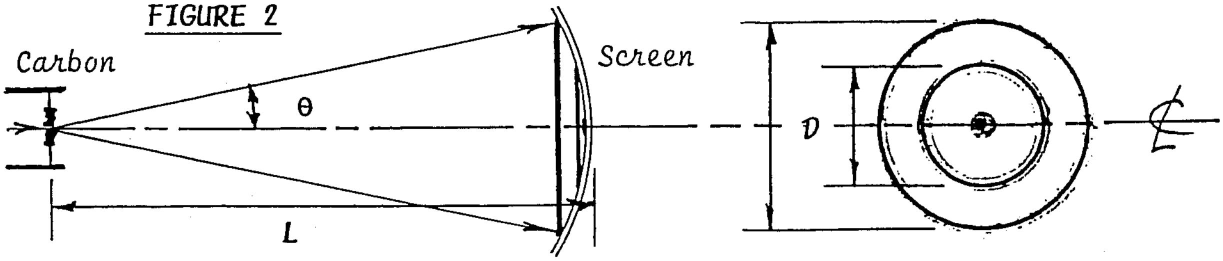
In 1912, **Prof. Max von Laue** had suggested, in connection with X-ray studies, that if fine gratings could not be made by man because of the basic granularity of matter, then perhaps this very granularity might provide a suitable grating. **Sir Lawrence Bragg** used the cubic system of NaCl to calculate interatomic spacings and showed them to be of the right order for X-rays. This salt, like most salts, is not suitable for sealing into an evacuated tube; however Carbon is vacuum-stable and can be formed in many different ways.

A similar calculation can be made using Carbon and assuming that its atomic system is also cubic; 12 gms of Carbon contain 6×10^{23} atoms (Avogradro's Number); the density of Carbon is about 2 gms/cm^3, 1 cm^3 contains 10^{23} atoms so that adjacent Carbon atoms will be about $^3/_{10}$ or a little over 0.2 nm apart. It is thus reasonable to expect that Carbon should provide a grating of suitable spacing for an experiment.

The nature of the effect to be observed however is not evident from these calculations; before proceeding with the electron diffraction experiment it is recommended that students are prepared for the probable results by observing an Optical Analogue such as TEL.555A.

Connect the tube TEL.555 into the circuit shown in Fig. 1, switch on the heater supply and wait one minute for the cathode to heat stabilise. Adjust the E.H.T setting to 4.0 kV.

FIGURE 2



Two prominent rings about a central spot are observed, the radius of the inner ring being in fair agreement with the calculated value of 14 mm. Variation of the anode voltage causes a change in diameter, a decrease in voltage resulting in an increase in diameter. This is in accord with de Broglie's suggestion that wavelength increases with decrease in momentum. Evidence of the particulate nature of the electron has been previously obtained and so this demonstration, which so closely resembles the optical one, reveals the **dual nature** of the electron.

The de Broglie wavelength of a material particle is

$$\lambda = \frac{h}{m v} \qquad \ldots \quad \ldots \quad \ldots \qquad 23.1$$

where h is Planck's constant. The velocity, v can be obtained from the classical expression

$$e V_a = \tfrac{1}{2} m v^2 \qquad \ldots \quad \ldots \quad \ldots \qquad 23.2$$

and substituted into the de Broglie relation, obtaining

$$\lambda = \frac{h}{m v} = \frac{h}{\sqrt{2 e m V_a}} = 1.23 \; V_a^{-\frac{1}{2}} \text{ nm} \qquad \ldots \quad \ldots \qquad 23.3$$

The condition for diffraction for small angles is

$$\lambda = d\Theta \qquad \ldots \qquad \ldots \qquad \ldots \qquad 23.4$$

where the small angle Θ can be calculated from the geometrical relationship of Figure 2 as

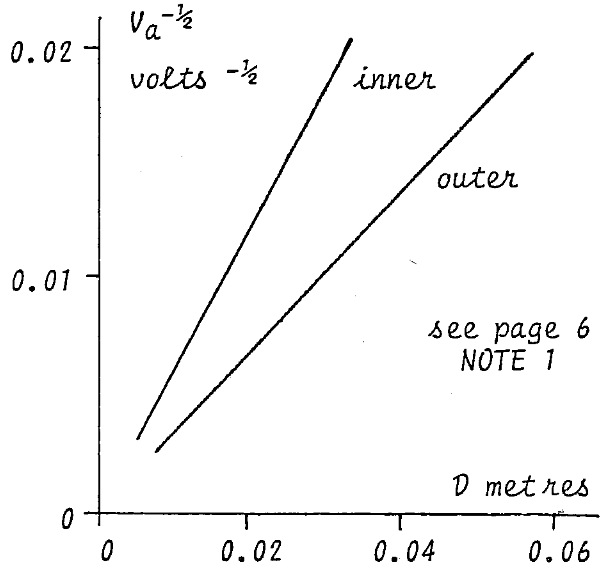
$$\Theta = \frac{D/2}{L} \qquad \ldots \qquad \ldots \qquad \ldots \qquad 23.5$$

and so from 23.3

$$D \cdot \frac{d}{2L} = 1.23\ V_a^{-\frac{1}{2}} \qquad \ldots \qquad \ldots \qquad 23.6$$

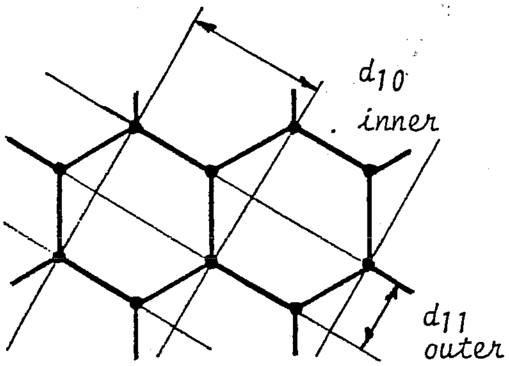
D and V_a are the only variables; tabulate D for different anode voltages V_a and plot the graph D proportional to $V_a^{-\frac{1}{2}}$.

V_a	$V_a^{-\frac{1}{2}}$	D metres	
kV	volts $^{-\frac{1}{2}}$	inner	outer
2.5	0.0200		
3.0	0.0183		
3.5	0.0169		
4.0	0.0158		
4.5	0.0149		
5.0	0.0141		
5.5	0.0135		
6.0	0.0129		



see page 6
NOTE 1

Measure the pathlength from the Carbon target at the gun exit aperture to the luminescent screen, L m, as accurately as possible using a back-reflection technique (**0.140 ± 0.003 m**).



Rearrange the equation 23.6 to evaluate interatomic spacings d using the gradients of the graphs of the outer and inner circles; compare with the established figures of d_{11} (0.123) and d_{10} (0.213) nm.

These results verify the theory and substantiate the de Broglie hypothesis; note that the ratio of the spacings is √3:1 which suggests that the arrangement of the Carbon atoms is more likely to be hexagonal rather than the assumed cubic.

NOTE : GRAPHICAL CONSTRUCTION.

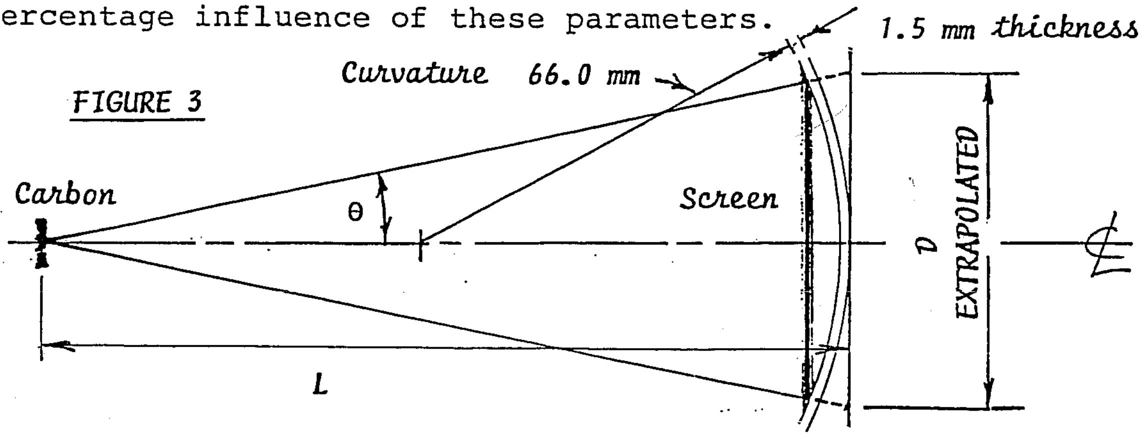
The convention of proportionality has been inverted for the purposes of this graphical construction in order to facilitate the calculations of d_{11} and d_{10} from the gradients of the respective lines.

The accuracy of these calculations depends on the length of the gradient line and the caliper measurement of the ring diameters.

NOTE : MEASUREMENT OF RING DIAMETERS.

For maximum accuracy the ring diameter should be extrapolated as in Figure 3 in order to compensate for both the curvature and the thickness of the glass envelope; the lower the anode voltage, the larger the ring diameter and the greater the percentage influence of these parameters.

FIGURE 3



UNIVERSAL STAND. TEL 501.

The Universal Stand has been designed to accomodate the whole range of Teltron Tubes and many other accessories and instruments.

The manner in which the Stand "offers" the experimental zone to the student is clearly illustrated in Figure 1. There is unimpeded access to all plug and socket connections; the horizontal centre line of the experimental zone is 25 cm from the bench top.

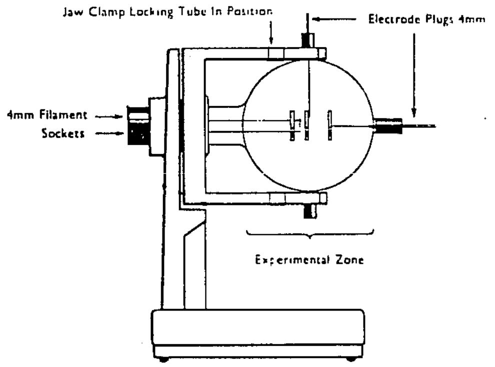


FIGURE I CLEAR PRESENTATION OF A MOUNTED TUBE

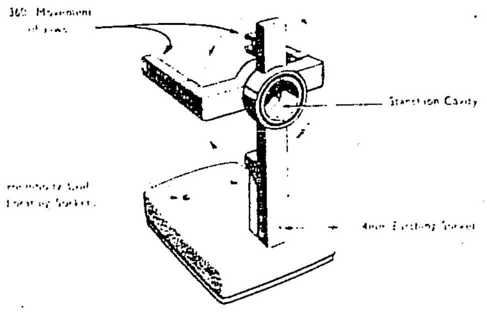


FIGURE 2 VERSATILITY OF STAND

Figure 2 shows the many locating and mounting positions available. The jaws can be rotated about a horizontal axis, which also passes through the cavity in the stanchion. Helmholtz coils and other accessories are mounted in the locating sockets on the base plinth.

The plinth (24cm x 18cm x 5cm), from which projects the stanchion (28 cm), is stove enamelled in Teltron Blue and cast in light alloy metal. Three rubber feet provide non-slip flat mounting. The handle, covered in black imitation leather, is located in a natural hazard free position.

The jaws, 16 cm long and 14 cm apart, are moulded in grey 'Delrin' plastic (Du Pont registered trade mark), this durable and heat resisting material also providing very high electrical insulation in the regions where supplies are connected to the experiments. With a slight amount of pressure each jaw opens to trap the bosses on the experimental instruments. The Jaw Clamps can now be slid forward.

The stand is normally supplied assembled, but the retaining hard-rubber 'O' ring can be easily removed by inserting a screwdriver into slots visible inside the stanchion cavity.

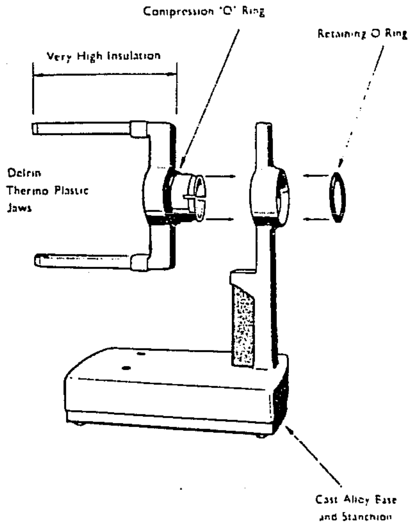


FIGURE 3 ASSEMBLY OF STAND AND JAWS

TELTRON LIMITED

Unit 14. 98 Victoria Road London NW10 6NB
Telephone 01-453 1224 (4 lines)

The TELTRON 4mm LEAD SET, TEL 500, is a convenient selection of highest quality 4mm connectors, sufficient for all wiring to be made between Series 'A' Tubes, power supplies, meters, rheostats, etc.

Specification.

Number supplied	Item	Length	Colour	Termination 1	Termination 2
2	Cables	100 cm	Green	Plug	Plug
1	Cable	75 cm	Black	Plug	Plug
1	Cable	75 cm	Red	Plug	Plug
2	Cables	50 cm	Black	Plug	Plug
2	Cables	50 cm	Red	Plug	Plug
1	Cable	25 cm	Green	Plug	Plug
1	Cable	75 cm	Green	Plug	Socket
1	Cable	75 cm	Black	Plug	Socket
2	Cables	75 cm	Red	Plug	Socket
2	Plugs		Black		
2	Plugs		Red		
2	Free Sockets		Black		
2	Free Sockets		Red		

Each cable contains 259 strands of 0.07mm dia. wire covered with a double layer of p.v.c. providing exceptional flexibility, insulation and current carrying capacity.

The plug and socket terminations are moulded integrally with the outer p.v.c. of the cable insulation.

The plugs are stackable and comprise a cluster of six silver-plated conductors with a special end-cap to prevent splaying. The cable enters the side of the plug.

2	Spade Coupler		Black		
2	Spade Coupler		Red		
1	4mm Coupler		Black		
1	4mm Coupler		Red		

This selection of couplers enables additional leads to be made up and facilitates connection to other apparatus. The spade coupler can be used to adapt a screw-type terminal to become a 4 mm socket and hence receive standard plugs; the 4 mm couplers are double-ended sockets and can be used to construct long leads or to rapidly convert a plug to a socket as required.

TELTRON

Atomic Physics Educational Apparatus

TEL 800 L.T. Power Unit

This unit is a dual metered general purpose laboratory power supply particularly suitable for operating the Teltron Coils, TEL 502 and 507.

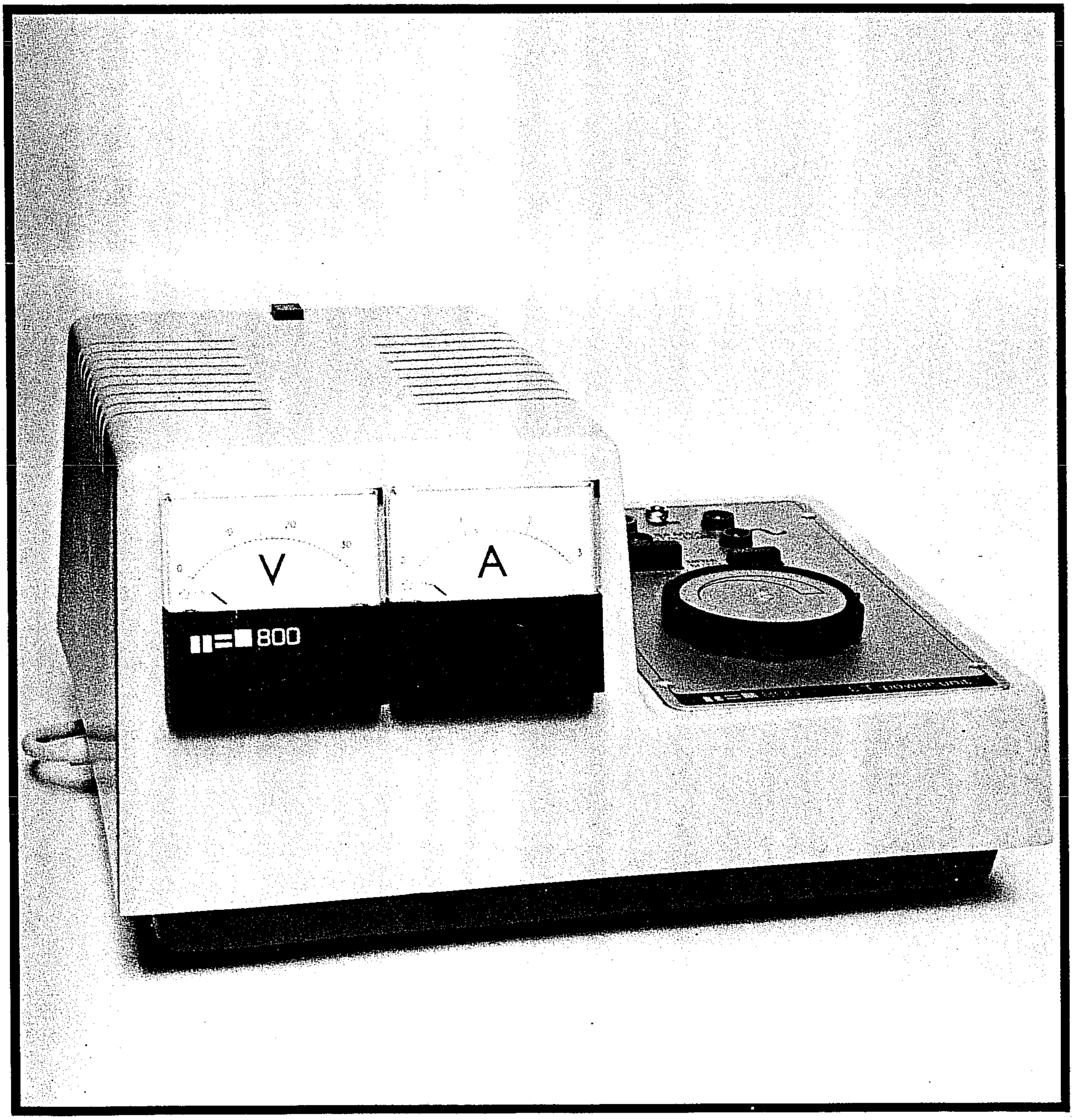
Power Output
0-30V, AC or DC (Ripple ≃ 10%)
Maximum total load, 3 Amperes.

Metering
1) AMPS: 0-3A, AC/DC.
2) VOLTS: 0-30V, AC/DC.
Each scale:
length 52mm, 100μA linear.

Power Input
110, 220, 240V, ±10%, 50/60 Hz.
Power Selector
Situated underneath.
Power On Neon indicator lamp.

General
Housing: Glass fibre reinforced resin moulding on cast aluminium base.
Ambient Temp: 35°C (95°F) max.
Dimensions
W: 280; D: 230; H: 150mm.
Weight: 6.6Kg.

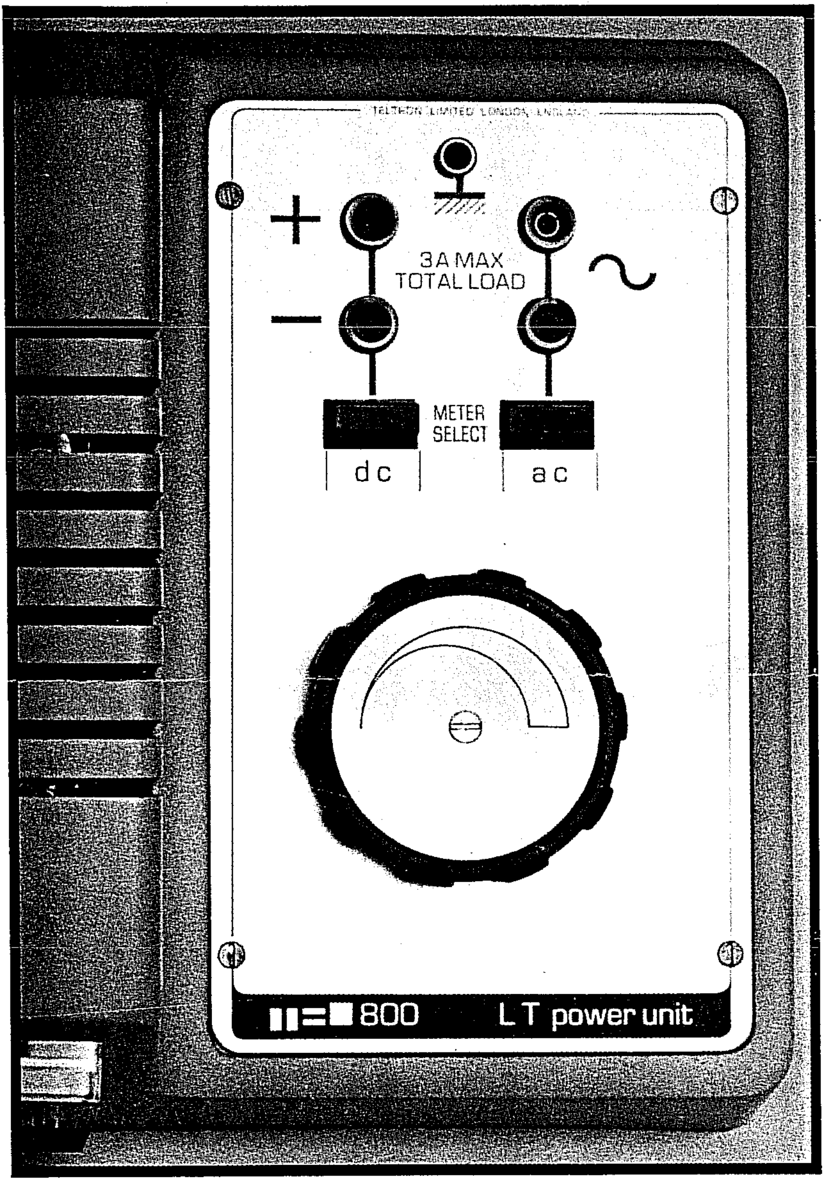
See control layout overleaf



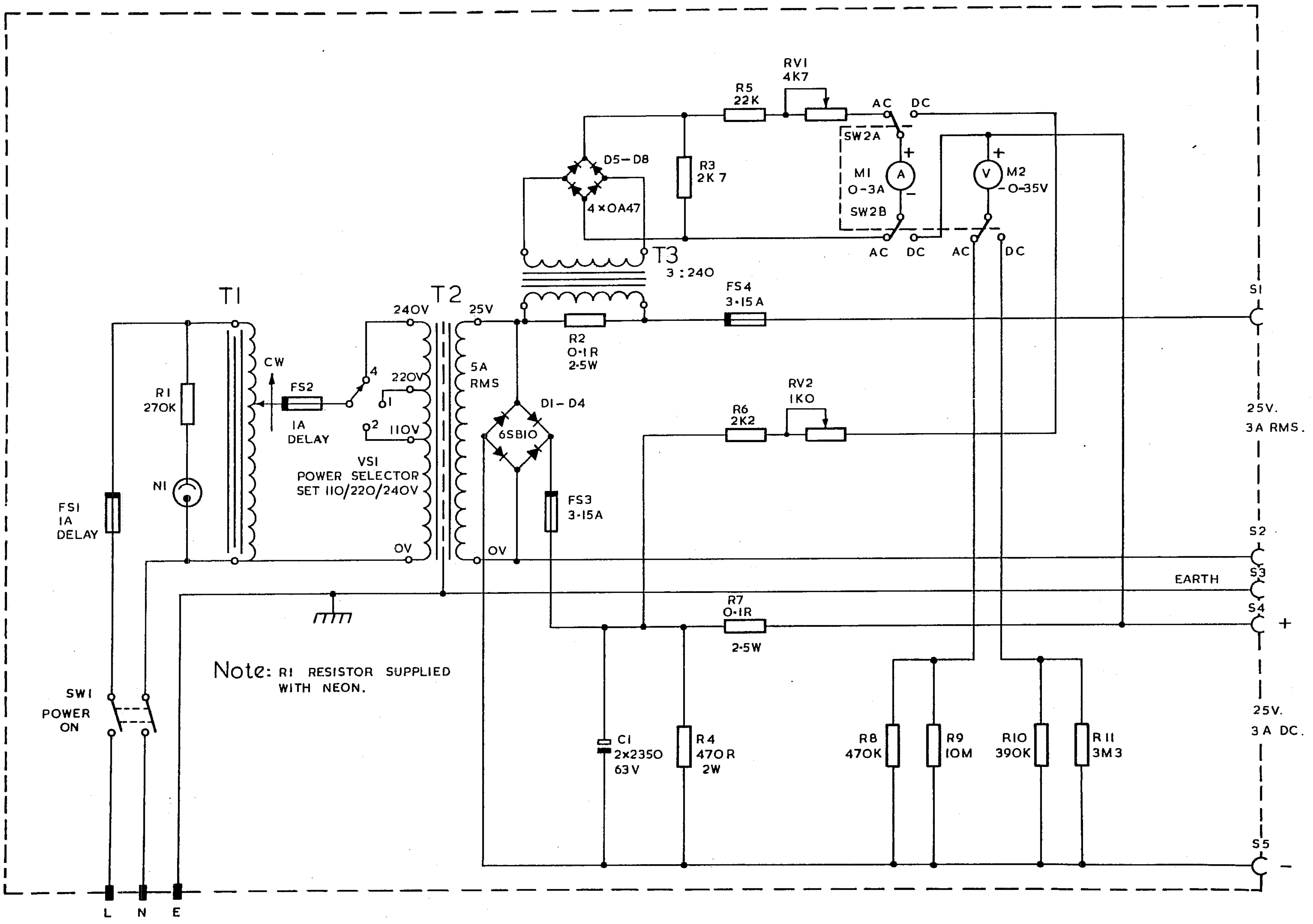
TEL 800 L.T. Power Unit

Controls
Meter Function Selector
Two press-button switches, interlocked, selecting AC or DC.
Voltage Control
Rotary movement, variable 0-30V.
Power On/Off Switch
Situated at back.

Connections
DC Output — 2 × 4mm Sockets.
AC Output — 2 × 4mm Sockets.
Earth — 1 × 4mm Socket.
Mains Cable —
Integral, 2 metres long.



Teltron Ltd 32/36 Telford Way London W3 7XD Tel: 01-743 0103
March 1975
Printed in England



Note: R1 RESISTOR SUPPLIED WITH NEON.

L.T. POWER UNIT. TEL 800 - CIRCUIT DIAGRAM

The packaging of the instrument has been carefully designed to ensure that units are delivered in the same condition as they leave the factory.

If any damage is apparent when the packing case is opened, the supplier of the equipment should be notified immediately and the instrument should not be used.

2.0 INITIAL CHECKS

Lift the instrument out of the box and remove all packing materials, including the plastic bag which contains the power supply lead and spare fuses.

Attach a plug to the power supply cable in accordance with the wiring instruction sheet.

Tilt the instrument onto its side and ensure that the Power Selector on the underside of the instrument indicates the correct mains voltage; to readjust the selector pull out the black plug and replace, with the arrow pointing towards the legend which corresponds to the power supply available in the laboratory.

Check that the Power Fuse and the other fuses are securely screwed in. Connect the mains supply to the unit by depressing the Power On switch (WHITE) on the back panel. When this is performed, the Power On lamp (RED) will be illuminated and the voltmeter will indicate a voltage provided that the voltage control has been advanced and one of the push button switches is depressed.

3.0 OPERATING INSTRUCTIONS

Having completed the initial checks of the unit the operation will become self-evident.

The DC output sockets and AC output sockets are clearly labelled.

N.B. It is most important that the total load of 3 amps maximum is never exceeded.
This means that if the D.C. load is 2 amps another 1 amp A.C. may be taken out at the equivalent A.C. voltage available. If the AC or DC load is 3 amps the other pair of output sockets should be left unconnected. The two pushbutton switches select either AC or DC measurements of both voltage and current.

The rotary voltage control increases voltage, AC or DC, when rotated clockwise.

The normal operational sequence would be as follows: Turn voltage control fully anti-clockwise. Switch off. Connect required load to output sockets. Select appropriate meter ranges. Depress Power On switch. Turn voltage Control clockwise to give required voltage and/or current. If this procedure is not followed it is possible to rupture some fuselinks with loads which give very high switching on current surges, such as the 'hairpin' filaments of some of the Teltron Tubes.

3.1 OPERATING TEMPERATURE

The instrument is designed to operate at ambient temperatures of up to 35°C (95°F) Max.

It is convection and radiation cooled, the heavy aluminium alloy base acting as a massive heat sink and cooled by the air drawn in through the gap between the cover and the base around the perimeter and expelled through the slots at the top of the cover.

mounting surface of the bench or a table is left unobstructed to allow free air circulation.

4.0 SERVICING AND MAINTENANCE

As with all Teltron equipment the L.T. power unit has been designed to withstand the abuse and misuse which all apparatus used for course demonstration and student practical work traditionally experiences and it will operate for long periods without the need for maintenance. Some items however will require attention at some time during the useful life of the instrument - the indicator lamp and the fuses.

4.1 ACCESS TO THE ELECTRONIC COMPONENTS

Switch off and disconnect.
Remove the screw retaining the large voltage control knob. Remove the knob by lifting it upwards. (It may be necessary to tap the knob with the screwdriver handle). Invert the instrument onto a piece of soft cloth and remove the four screws fixing the cover to the base. Hold the cover and the base together and invert the unit again putting it down in its normal upright position, lift the cover carefully and rotating it as if it was hinged at the back of the unit let it rest with the Power On switch in the off position.
All electronic components are now accessible.

4.2 REPLACEMENT OF 'POWER ON' INDICATOR LAMP

Each lampholder is an integral unit containing a permanently fixed neon with a resistor within the red plastic lampholder. Unsolder the two leads and push out the whole assembly. Insert, push hard in a new indicator and reconnect the leads to the same points.

4.3 REPLACEMENT OF ALL FUSES

These are readily accessible on the underside of the instrument.

Note that the following fuselinks (see circuit diagram) are required as replacements:

Power Fuse (FS1) - 1 amp, Anti-surge Type
Power Fuse (FS2) - 1 amp, Anti-surge Type
D.C. Output Fuse (FS3) - 3.15 amp, A/S Type
A.C. Output Fuse (FS4) - 3.15 amp, A/S Type

4.4 FAULT FINDING

It is recommended that unless professional facilities are available the rectification of only minor and obvious faults are attempted by the user; for correction of obscure faults the user should seek advice of the supplier.

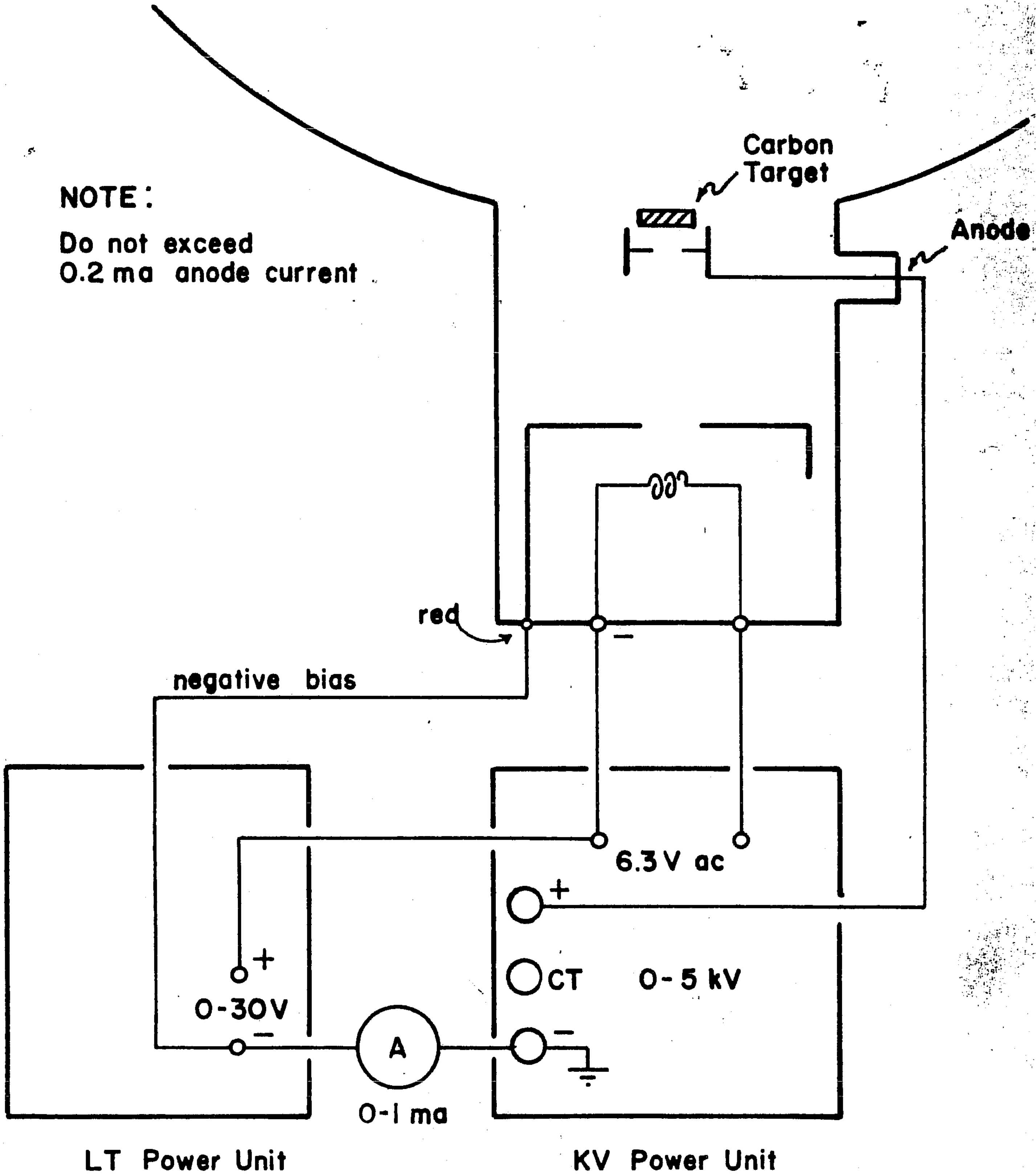
ELEMENTARY FAULTS

A. Indicator Lamp fails to operate but the voltmeter does indicate a voltage AC or DC when voltage control advanced.
Power indicator Lamp and/or associated wiring defective.

B. Indicator Lamp fails to operate and the voltmeter does not indicate a voltage AC or DC when voltage control advanced.
Mains plug defective.
Indicator Lamp and/or Power Fuse FS1 defective.

C. Voltmeter does not read AC or DC voltage but AC current indicated in the load.
DC output fuse defective, Power Rectifier Bridge defective; voltmeter defective.

D. Voltmeter reads both AC and DC voltage but no AC or DC current indicated in the load.
AC output fuse defective.
Wiring to the load defective; current meter defective.



"Electron Diffraction" Circuit