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Report

ELECTRICAL BREAKDOWN OF GASES IN THE PRESENCE OF A TRANSVERSE MAGNETIC FIELD

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ELECTRICAL BREAKDOWN OF GASES IN THE PRESENCE OF A TRANSVERSE MAGNETIC FIELD

by

H. Blevin

ABSTRACT

An explanation is given for the double-valued sparking potential curves observed for low pressure gas breakdown in the presence of a transverse magnetic field. In accordance with theory, experiments show that there is a range of magnetic field values for which gas breakdown can only occur between co-axial cylinders when the inner cylinder is positive. Such a device can be used for high voltage rectification.

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1. Introduction

Measurements (1, 2, 3) of the sparking potential U in the presence of a transverse magnetic field H show a double-valued sparking potential curve U vs Hd (d is the electrode separation) for a certain range of magnetic field strengths provided the gas pressure p is sufficiently low. This feature of the breakdown curve has been attributed (2, 3, 4) to a maximum in the α/p vs E/p curve for a given magnetic field strength (α is the first Townsend ionization coefficient, E is the electric field strength). The decrease in α/p for large E/p values is expected to occur because the total number of collisions made by an electron when crossing the gap decreases as E/p increases. The presence of a maximum in the ionization efficiency curve will have a contributary effect also. However, a maximum value for α/p in the absence of a magnetic field would also be expected since in this case the number of collisions made in crossing the gap for a given pressure is inversely proportional to E/p (5). On the above reasoning a double-valued Paschen curve $U = f(pd)$ would result. This type of curve has only been observed (6) for helium, whereas in the presence of a transverse magnetic field the double-valued characteristic is obtained for all gases for which measurements have been carried out. Evidently the existence of a maximum in the α/p vs E/p curve is not in itself sufficient to explain the observed breakdown characteristics.

2. Theory of Gas Breakdown for large E/p values

A quantitative evaluation of sparking potentials for low pd values requires a knowledge of α/p as a function of E/p for high values of this parameter. However there are no reliable measurements of α/p in this range (7) and a general relation for α/p will be assumed in this analysis. As far as assessing the effect of a maximum in the α/p vs E/p curve upon the general trend of the breakdown characteristic is concerned it is found that the results remain qualitatively similar whatever functional relationship for α/p is assumed.

(a) No magnetic field

If $\alpha/p = f(E/p)$, then the breakdown criterion $\alpha d = \ln(1 + \frac{1}{\omega/\alpha})$ becomes:

$$pd.f\left(\frac{U}{pd}\right) = \ln\left(1 + \frac{1}{\omega/\alpha}\right),$$ where ω/α is the second Townsend coefficient.

It follows that $\frac{dU}{d(pd)}$ is negative only if

$$0 < (E/p)x + (E/p)f'/f < 1 \qquad \ldots\ldots\ldots (1)$$

where $x = \frac{d(\omega/\alpha)}{d(E/f)} \Big/ (\omega/\alpha)(1 + \omega/\alpha)\ln\left(1 + \frac{1}{\omega/\alpha}\right)$

and $f' = \frac{df}{d(E/p)}$.

Now $(E/p)f'/f > 1$ for E/p less than the Stoletow constant

< 1 for E/p greater than the Stoletow constant

< 0 for E/p greater than (E/p) max. corresponding to the maximum value of α/p.

The inequality (1) shows that for small E/p values, $\frac{dU}{d(pd)}$ is positive corresponding to the branch of the Paschen curve to the right of the minimum which occurs when $(E/p)x + (E/p)f'/f = 1$. For higher E/p values the Paschen curve has a negative slope which is maintained provided $(E/p)x + (E/p)f'/f$ remains within the limits indicated and the normal Paschen curve results. When x is sufficiently small (or negative) and f'/f becomes negative, the Paschen curve will bend back giving a second branch with positive slope. However the existence of a maximum in the α/p vs E/p curve does not necessarily mean that a double-valued Paschen curve will result.

(b) Magnetic field present.

It has been shown previously (5) that the presence of a transverse magnetic field has the same effect on α as would an increase in the gas pressure so that the sparking criterion becomes:

$$p'd\, f\left(\frac{U}{p'd}\right) = \ln\left(1 + \frac{1}{\omega/\alpha}\right),$$

where the equivalent pressure $p' = p\sqrt{1 + C(H/p)^2}$, C being a constant. For low pressure breakdown as considered here $p' = \sqrt{C}\, H$ so that proceeding as before it is found that $\frac{dU}{d(Hd)}$ is negative only if

$$0 < (E/p')x' + (E/p')f'/f < 1 \qquad \ldots\ldots\ldots (2)$$

where $$x' = \frac{d(\omega/\alpha)}{d(E/p')} \Big/ (\omega/\alpha)\,(1 + \omega/\alpha)\,\ln\left(1 + \frac{1}{\omega/\alpha}\right),$$

and $$f' = \frac{df}{d(E/p')}$$

As for the case when there is no magnetic field present it would appear that the double-valued sparking characteristic can only occur if there is a somewhat restricted dependence of ω/α upon E/p. Although in the presence of a transverse magnetic field ω/α will have a markedly different dependence upon the electric field strength (5), the occurrence of this double-valued characteristic for all gases used in experiments carried out so far suggests that a different explanation is required.

For high values of $U/(Hd)^2$ the height h $(= 11.36\, E/H^2)$ of an electron's cycloidal path in uniform fields becomes comparable to the electrode separation d and electrons colliding within a distance h of the anode will be captured there before they can complete a cycloidal arch. At low pressures these electrons make an insignificant number of collisions and are unable to produce further ionization. Consequently there is no α applicable to these electrons and the breakdown criterion becomes:

$$(d - h) = \ln\left(1 + \frac{1}{\omega/\alpha}\right).$$

Proceeding as before it is found that $\frac{dU}{d(Hd)}$ is negative only if

$$\frac{h/d}{1 - h/d} < (E/p')x' + (E/p')f'/f < \frac{1 + h/d}{1 - h/d} \qquad \ldots\ldots\ldots (3)$$

As Hd decreases the sparking potential passes through a minimum when $(E/p')x' + (E/p')f'/f = \frac{1 + h/d}{1 - h/d}$ and the U vs Hd curve then has a negative slope. Unlike the case outlined above, this trend cannot be maintained for finite values of x' because of the rapid increase of the lower limit in expression (3). This factor becomes infinite when $h = d$, or when electrons leaving the cathode are captured by the anode before they are able to complete a cycloidal arch. The relation $h = d$ is shown in Fig.1, and the sparking potential curve must lie to the right of this unless the electric field is so large that sparking is governed by electrode processes only.

For high E/p' values, α/p' will no longer be a function of E/p' alone due to the inability of the electrons to reach an equilibrium velocity distribution. In these circumstances a quantitative treatment becomes very difficult, but the limiting curve $h = d$ of Fig.1 will be retained.

3. Breakdown with Concentric Cylindrical Electrodes

In the presence of a transverse magnetic field a plane parallel electrode system is not suitable for sparking potential measurements at low pd values due to the lateral loss of electrons. This loss can be eliminated by using a concentric cylinder electrode system in an axial magnetic field. The limiting curve corresponding to $h = d$ in the plane case is readily calculated and for cylindrical geometry there is a polarity effect such that gas breakdown only occurs provided:

inner cylinder negative $$U < \frac{(r_2^2 - r_1^2)^2 H^2}{45.4\, r_2^2} \quad \text{........ (4)}$$

inner cylinder positive $$U < \frac{(r_2^2 - r_1^2)^2 H^2}{45.4\, r_1^2} \quad \text{........ (5)}$$

where r_1, r_2 are the radii of the inner and outer cylinders respectively. These equations do not apply for voltages greater than about 50 kV where relativistic effects become important.

For given values of r_2/r_1, and pd, the breakdown characteristics for both polarities are shown schematically in Fig.2. Provided the magnetic field is kept within the limits $(Hd)_0 < Hd < (Hd)_1$ indicated in Fig.2 it is evident that gas breakdown can only occur when the inner cylinder is positive. As pd is decreased both breakdown curves are displaced towards higher H and U values due to electron recapture at the cathode surface (4, 5).

4. Experimental results

Penning (1) and Haefer (2) have shown that diffusion of electrons along lines of magnetic force to the end walls of the discharge tube can influence the breakdown voltage at low gas pressures. In the experiments described here, non-uniform fields of the types shown in Fig.3 have been used to avoid this charge loss. Using a field geometry of Fig.3(a) the radial component of the magnetic field exerts an axial force on electrons which confines them in the region of maximum field strength when the inner cylinder is positive. For the reverse polarity electrons drift either to the end walls, or to a region where the axial magnetic field strength is sufficiently small so that electrons are captured at the anode. This field geometry is suitable for measuring breakdown potentials with the inner cylinder positive. The field geometry of Fig.3(b) confines the electrons in the region of weakest magnetic field when the inner cylinder is negative and a magnetic field of this type was used for measurements with this electrode polarity. Using a field of similar geometry to that shown in Fig.3(b) Strutt (8) observed that sparking could only be obtained with the inner cylinder negative.

For sparking potential measurements two discharge tubes were constructed with copper electrodes having the dimensions shown below.

	Tube 1	Tube 2
r_1	= 0.75 cm.	= 0.25 cm.
r_2	= 1.27 cm.	= 1.27 cm.
length	= 10.2 cm.	= 8.9 cm.

Measurements for dry air were made using magnetic field geometries as indicated above and are shown in Fig.4 and Fig.5. The magnetic field values correspond to the sparking region of the non-uniform fields. From Fig.5 it is seen that a discharge tube of this type is capable of rectifying high voltages provided the magnetic field strength is kept within a limited range. However, by using a non-uniform field of the kind shown in Fig.3(a) sparking can be prohibited when the inner cylinder is negative. It was found that sparking did not occur in either tube for this polarity with magnetic field strengths up to 800 oersted, the highest available with the present apparatus, and voltages up to 10 kV. In this way the range of magnetic field values for which rectification occurs can be greatly extended.

Alternating voltages (50 c/sec) up to 15 kV were rectified using Tube 1. ($p = 10^{-2}$ mm Hg) in a half-wave circuit. Observations of the output ripple confirmed that the tube fired every alternate half-cycle indicating that there were sufficient free electrons present to initiate breakdown without externally applied agencies.

Because there are no filament insulation problems, this type of rectifier is easily adaptable to a cascade multiplier arrangement, by using three or more concentric cylinders. Fig.6 shows the associated circuit and dimensions of a voltage doubler unit made in this way.

Both tubes 1 and 2 have been used as a clamping switch in the circuit of Fig.7 with currents up to 2,400 amps on a 12.5 kc/sec signal. The switch can be fired either before or after the first current maximum in the resonant circuit by changing the polarity of the connections to the tube. With the inner cylinder positive the voltage must be across the switch before the magnetic field is applied and the switch fires when the voltage is decreased. The applied magnetic field must not be large enough to cause sparking at the high initial voltage, but sufficient to cause breakdown at lower voltages (cf. Fig.4).

5. Conclusions

(i) It is shown that in the absence of a magnetic field the occurrence of a maximum in the α/p vs E/p curve does not necessarily mean that a double-valued sparking potential curve will result; the effect of such a maximum on the general trend of a Paschen curve can be masked by the dependence of the secondary coefficient ω/α upon E/p.

(ii) In the presence of a transverse magnetic field the double-valued curve U vs Hd occurring for low gas pressures is explained by electron capture at the anode before they are able to complete a cycloidal arch. Applying this theory to breakdown between co-axial cylinders shows that there is a range of magnetic field values for which sparking occurs for one electrode polarity only.

I am grateful to Mr. W. Millar for many helpful discussions and to Mr. R. Carter who helped with the experimental measurements.

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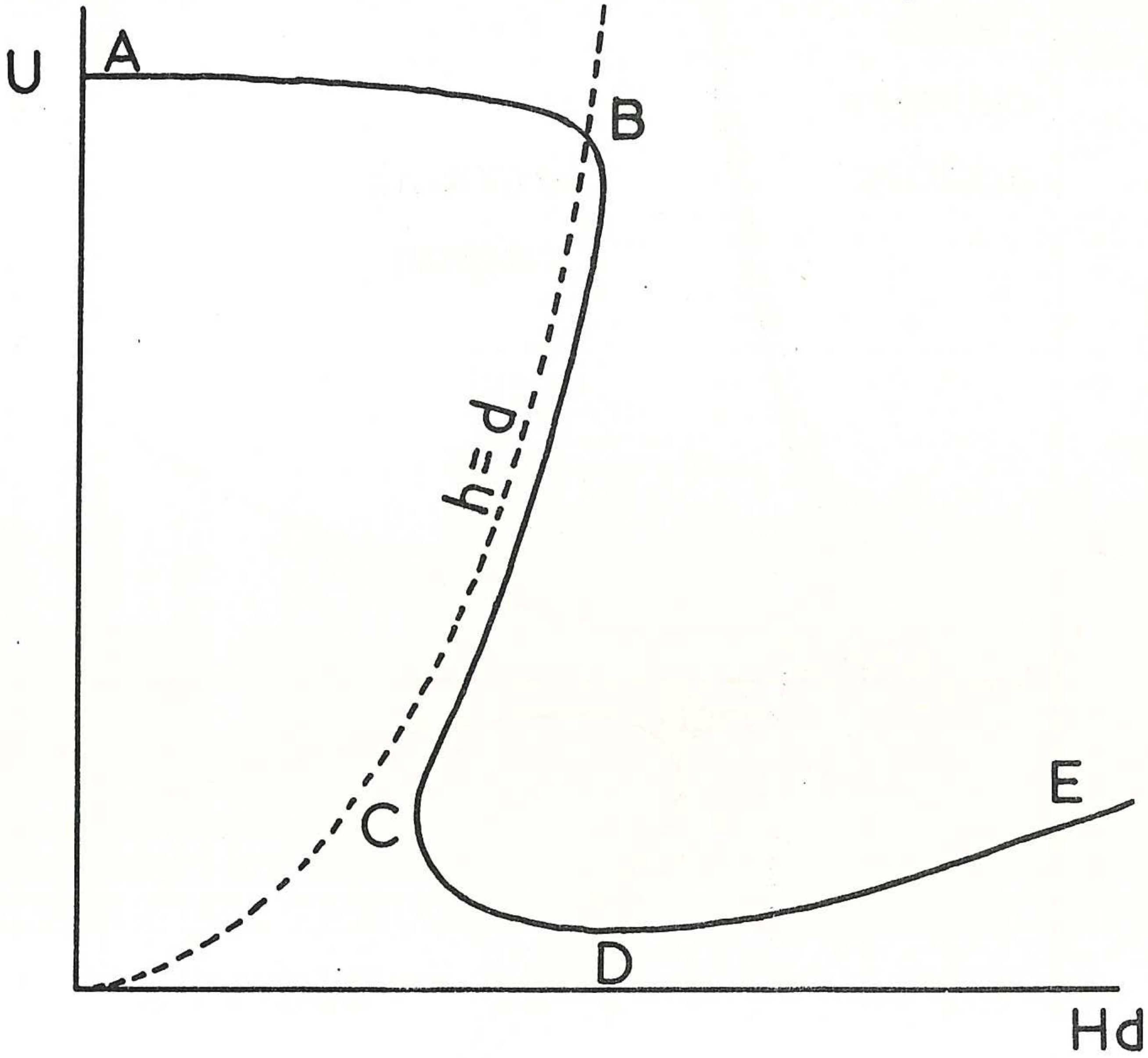


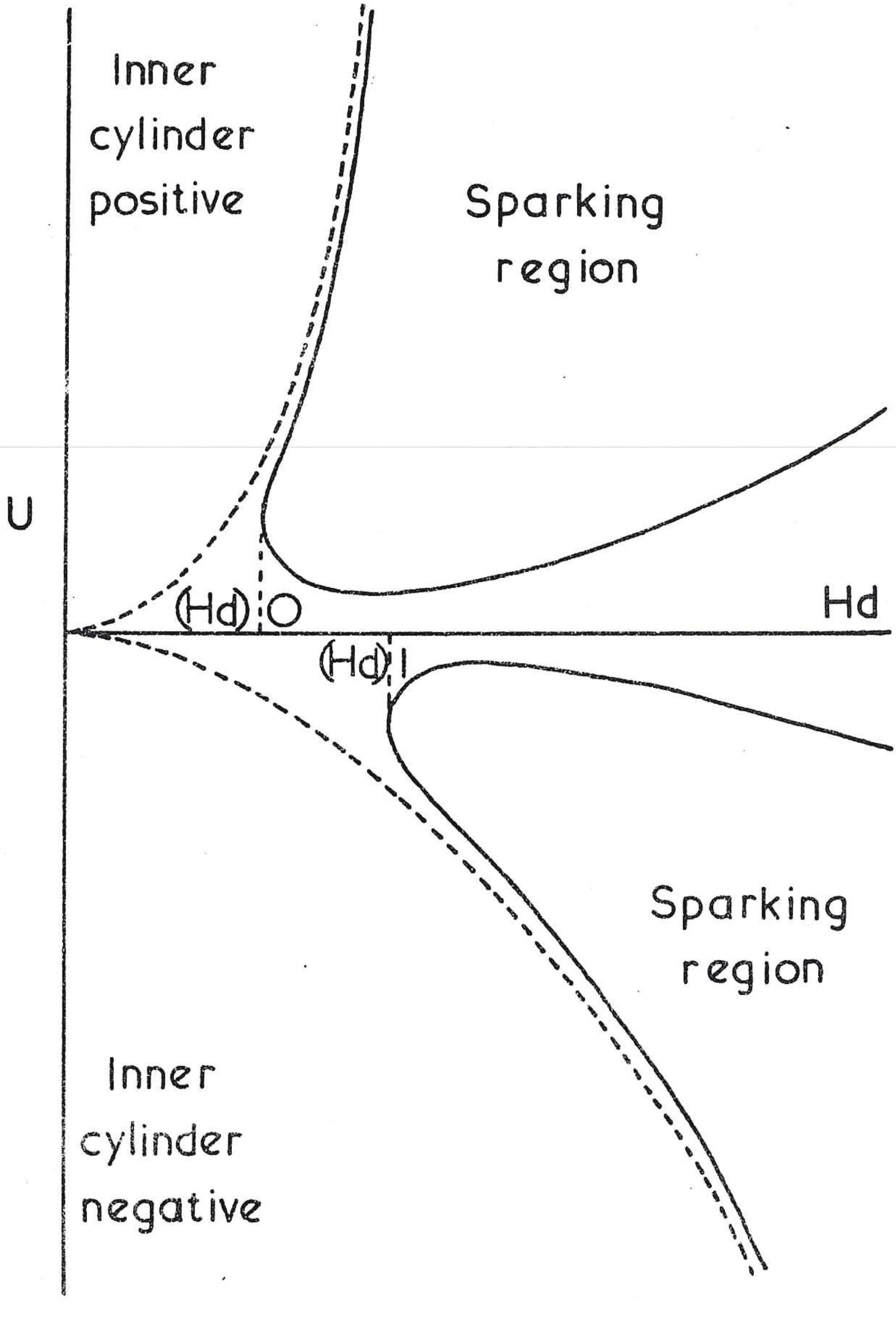
CLM/R 10 Fig. 1
Sparking potentials in a transverse magnetic field for low gas pressures
(sketch - not to scale)

Region A - B : electrode processes

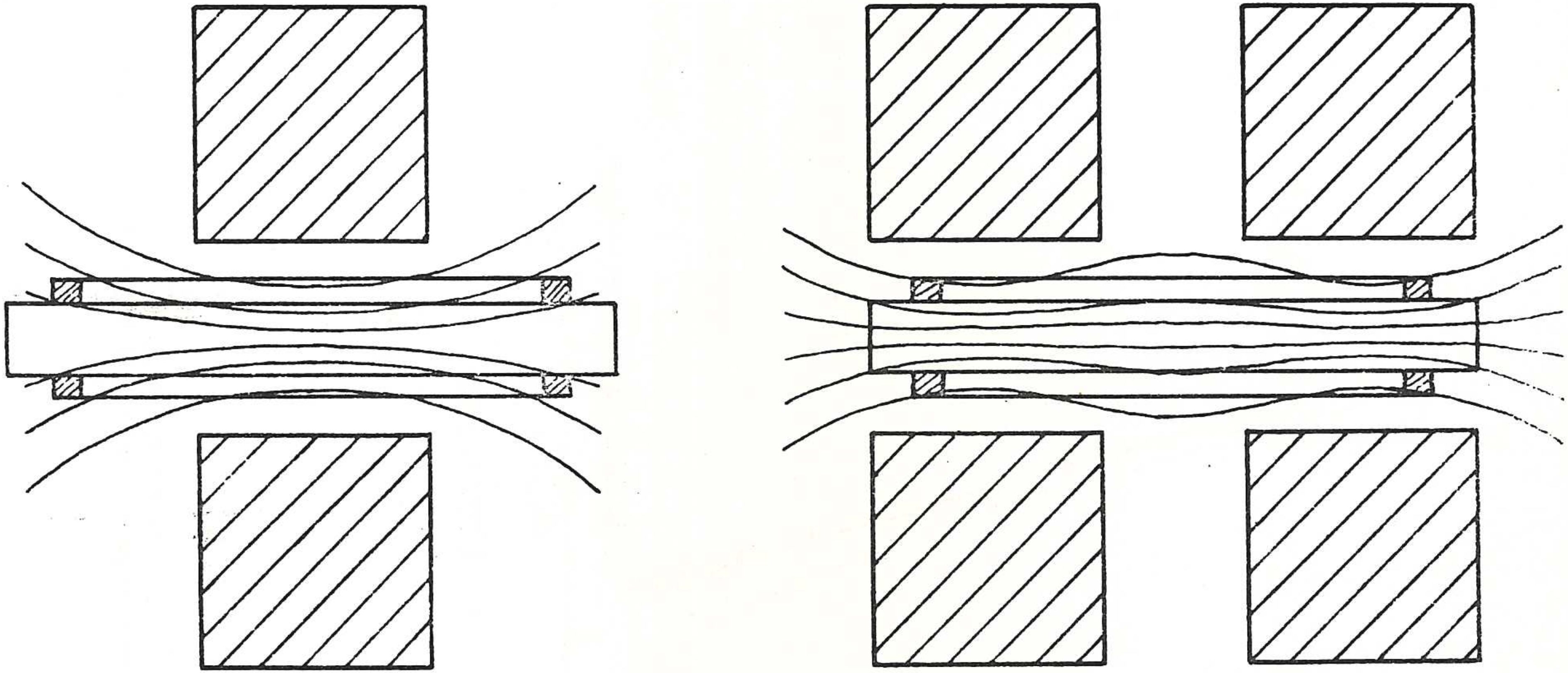
B - C : $\dfrac{h/d}{1 - h/d} > (E/p')x' + (E/p')f'/f$

C - D : $\dfrac{h/d}{1 - h/d} < (E/p')x' + (E/p')f'/f < \dfrac{1 + h/d}{1 - h/d}$

D - E : $(E/p')x' + (E/p')f'/f > \dfrac{1 + h/d}{1 - h/d}$



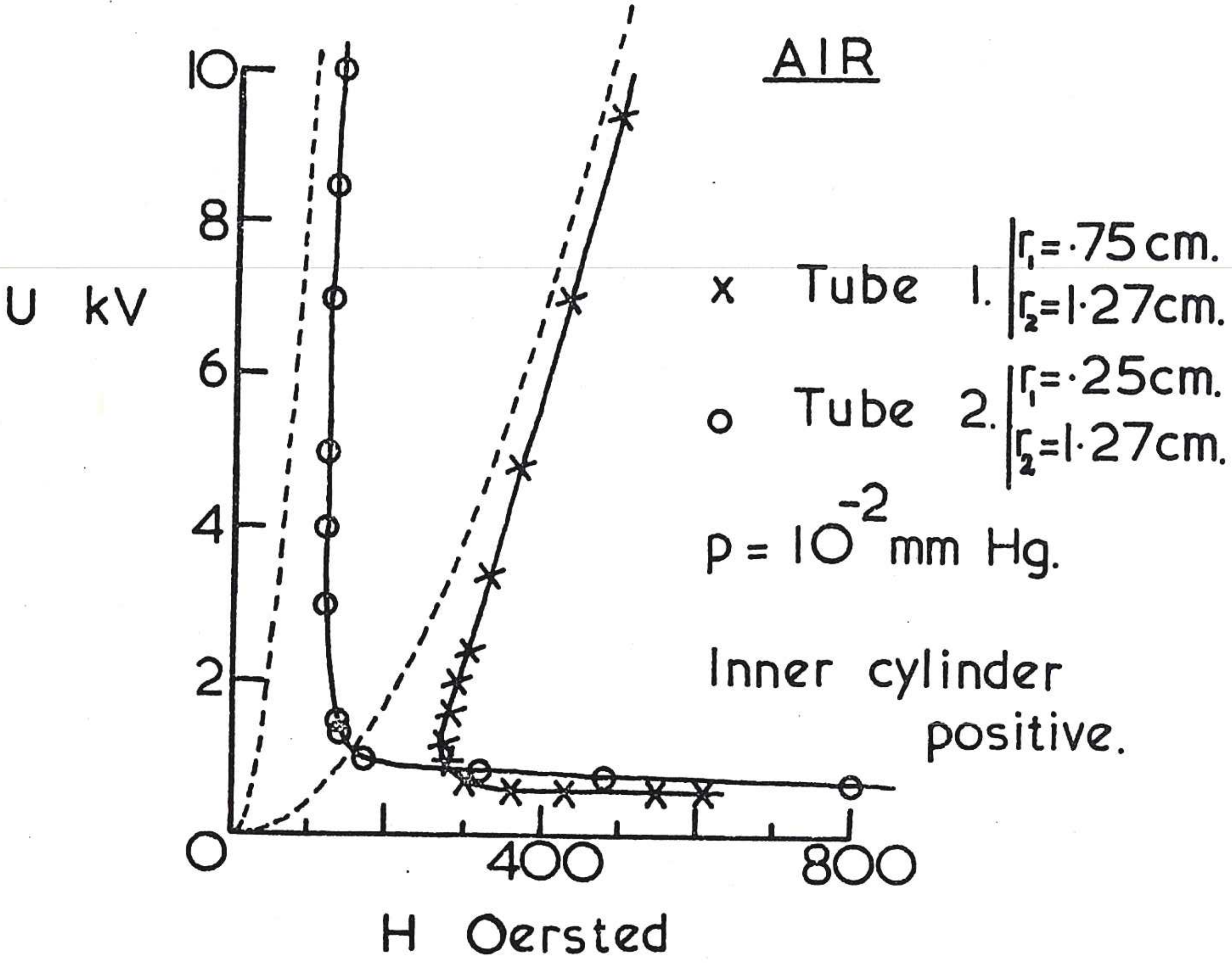
CLM/R 10 Fig. 2
Sparking potentials between co-axial cylinders in an axial magnetic field
(sketch - not to scale)



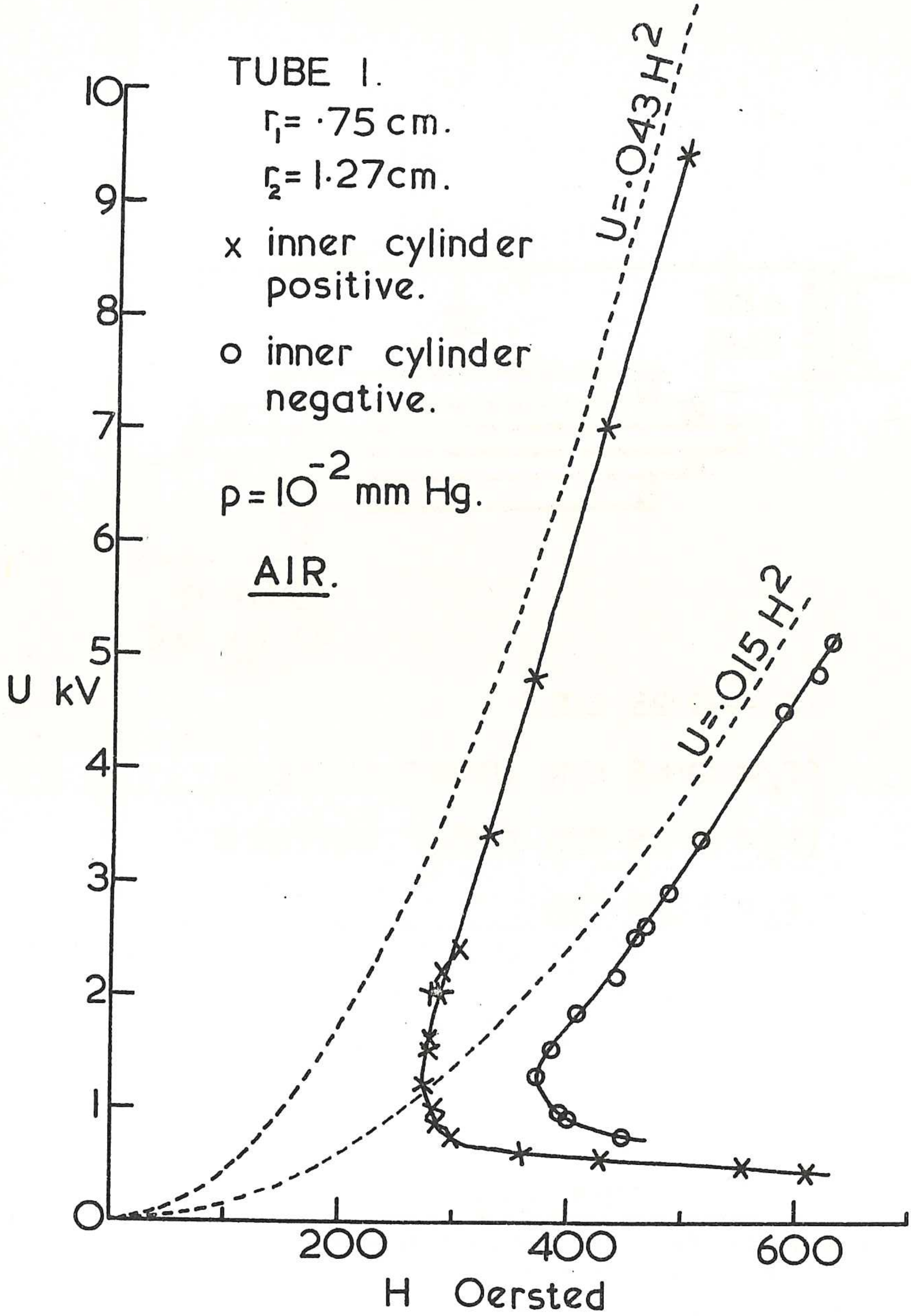
(a).

(b).

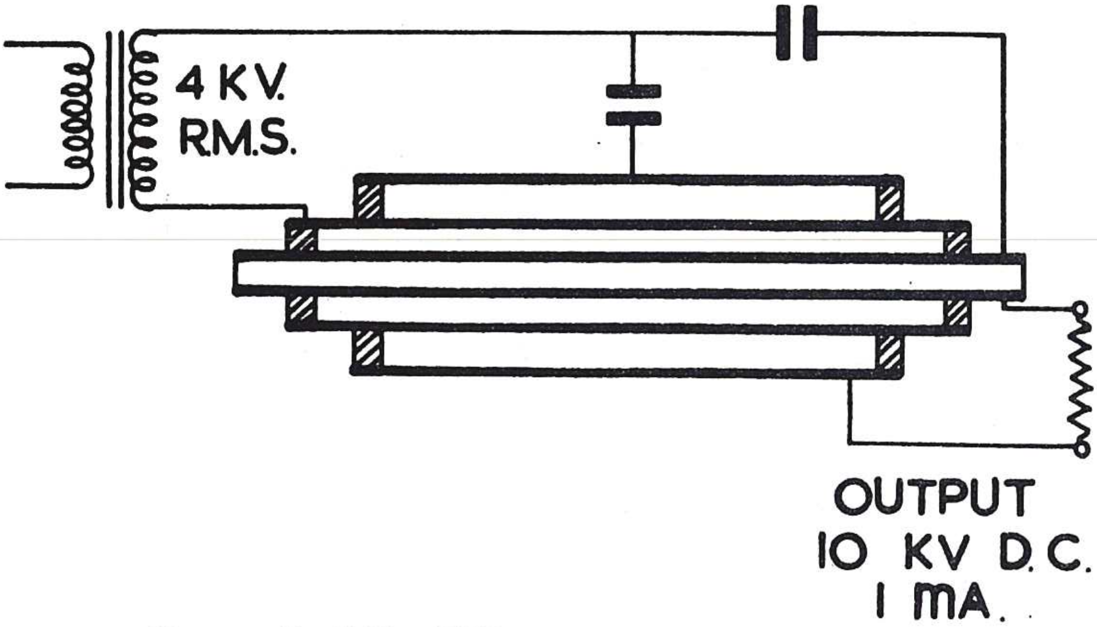
CLM/R 10 Fig. 3
Magnetic field configurations used for sparking potential measurements



CLM/R 10 Fig. 4
Sparking potentials for tubes 1 and 2 with the inner cylinder positive



CLM/R 10 Fig. 5
Sparking potentials for tube 1 showing polarity effect



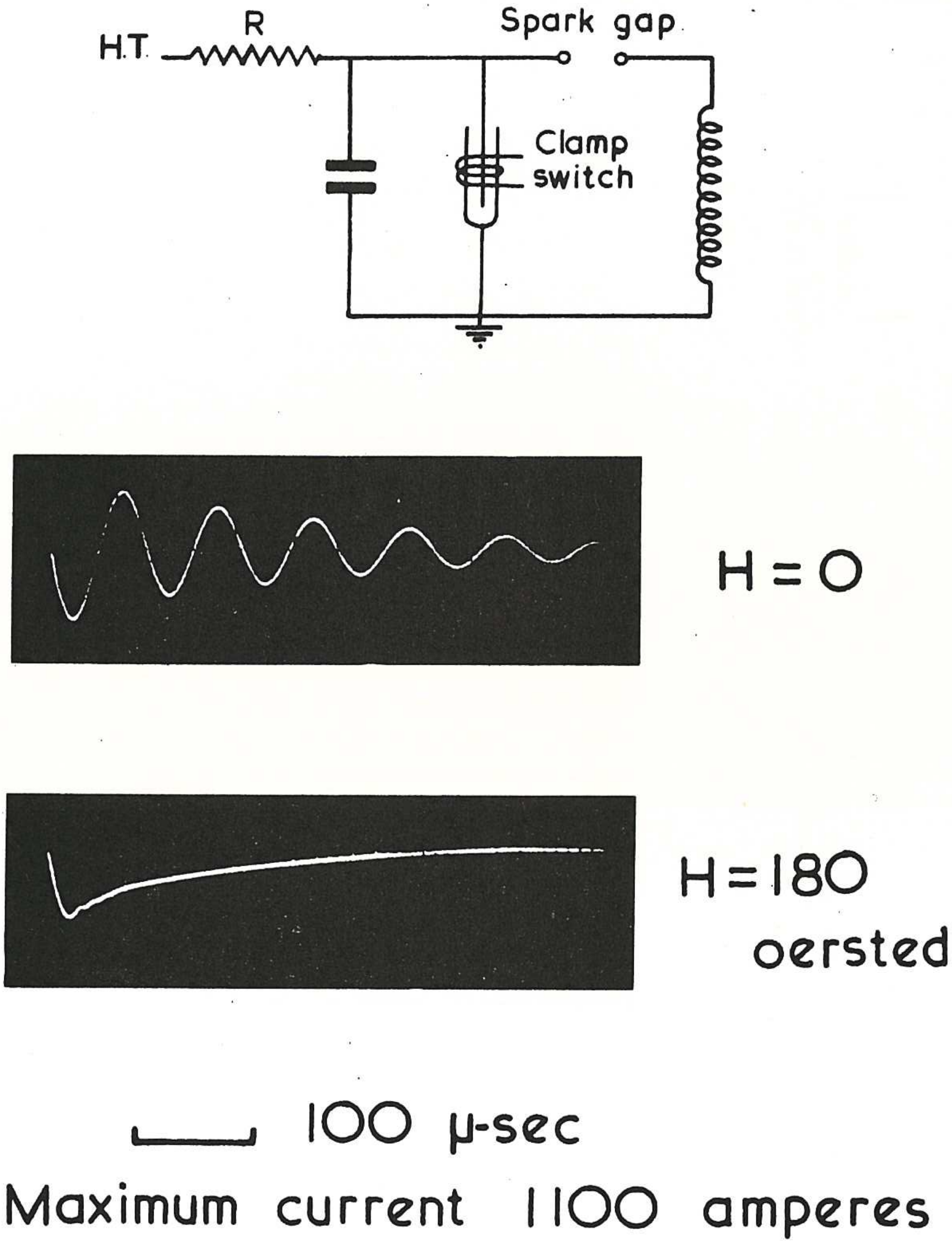
$r_1 = 0{\cdot}25$ cm.

$r_2 = 0{\cdot}65$ cm. inner surface

$r_2' = 0{\cdot}75$ cm. outer surface

$r_3 = 1{\cdot}27$ cm

CLM/R 10 Fig. 8
Voltage doubler unit. (H = 400 oersted)



CLM/R 10 Fig. 7
Clamping circuit and current characteristics

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