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The influence of a transverse magnetic field on a subnormal glow discharge in air

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Abstract. In subnormal glow discharge under d.c. excitation at different pressure in a varying transverse magnetic field (0 to 30 G) some measurements have been carried out for various initial average tube currents. The voltage across the discharge increases and average tube current and residual current decreases in the magnetic field. With the help of Beckman's expression [4] for the axial field and the electron density distribution in a transverse magnetic field the observed variation of current and voltage can be satisfactorily explained. The variation of axial electric field with transverse magnetic field can be represented to a fair degree of accuracy by the derived equation. The behaviour of residual current with magnetic field has been observed in these oscillations.

Keywords. Residual current; subnormal glow; electron density.

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1. Introduction

When a magnetic field acts upon a glow and arc plasma, various changes such as an increase of equivalent pressure, a change of radial ion and electron density and a marked change in the voltage-current characteristics take place. Some amount of work, both theoretical and experimental, has been done in a longitudinal magnetic field by Allis and Allen [1], Penning [2], Jana and Sen [3]. The effect of a transverse magnetic field on the positive column of a glow discharge has been studied by Beckman [4] and the variation of current in a variable transverse magnetic field has been studied by Sen and Gupta [5]. With regard to effect of transverse magnetic field on arc discharge, Allen [6], Sen and Das [7] observed voltage-current characteristics and showed that current gradually decreases and voltage across the arc increases with the increase of the magnetic field. Very little work has, however, been done on the nature of current-voltage characteristics and the associated residual current in subnormal discharge. Nema and Shrivastava [8] and Singh and Shrivastava [9] have investigated the nature of oscillations in the residual current in a subnormal glow discharge in air. Though Beckman's theory of the effect of a transverse magnetic field on the positive column is based on some assumptions which are partially valid, some are equally valid in case of subnormal, glow discharge. All concept has been made in this paper to test the validity of Beckman's theory in case of subnormal glow discharge. As the current consists of continuous pulses and the frequency of the pulses is comparatively

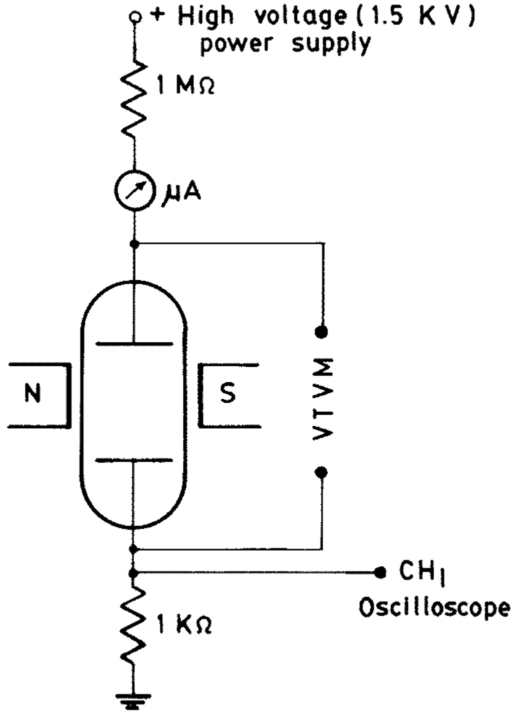

Figure 1. Experimental arrangements.

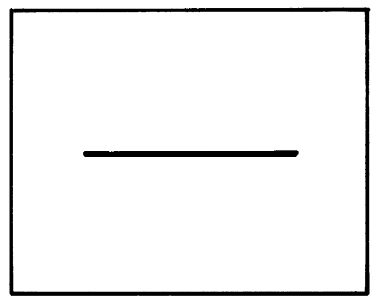

Figure 2. Straight line trace sweeps of both the channel initially coincide.

larger, the current may be considered as continuous. When dark to glow discharge transition takes place, the density of plasma is increased to find the nature of variation and to find whether the theory is developed in case of low current discharge. Regarding this the variation of current and voltage in transverse magnetic field can be extended to similar variation in the theory of subnormal discharge. Therefore, the present investigation has been undertaken and the present paper reports the results in the case of subnormal discharge in air under a variable transverse magnetic field.

2. Experimental procedure

Figure 1 shows the experimental arrangements. A d.c. source from a 1.5 kv regulated power supply with an insignificant ripple (of approximately 60 mv) was used to ionize the gas. The discharge tube was cylindrical of length 22 cm, diameter 4.0 cm and fitted with two internal electrodes (diameter 3 cm; separation between the electrodes 16.3 cm). The pressure was measured by a pirani vacuum gauge. The ballest resistor (1 MΩ) limited the discharge current and kept the HV unit within its current capacity. A 1 kΩ resistor was connected between the discharge tube and earth to provide a signal to the oscilloscope. A current meter (sensitivity ± 0.25 μA) was connected to measure the average discharge current

Table 1. Separation between the pole pieces = 4.5 cm; diameter of the pole pieces = 5 cm.

Current in mA	Corresponding magnetic field in Gauss (G)						Avg. magnetic field Gauss (G)
	Along the length			Along the breadth			
	Left	Centre	Right	Up	Centre	Down	
0	0	0	0	0	0	0	0
50	6	6	6	6	6	6	6
100	13	13	13	13	13	13	13
150	20	20	20	20	20	20	20
200	27	27	27	27	27	27	27
250	34	34	34	34	34	34	34
300	40	40	40	40	40	40	40

in the circuit. Voltage from the HV unit was applied to the discharge tube and gradually increased till air in the tube broke down. The voltage across the electrodes has been noted with a VTVM (sensitivity ±3 V). Both sweeps of the dual channel oscilloscope (Tektronix TDS 210) were initially made to overlap. The straight line trace, in figure 2 shows the position where sweeps of both the channels initially coincide. A transverse homogeneous magnetic field was provided by an electromagnet and extreme care was taken to ensure that the lines of force were perpendicular to the axis of the discharge tube. The field, variable from 0 to 30 G, was measured by a calibrated flux meter (sensitivity 2%).

To ascertain whether there is a variation of the applied magnetic field along the entire length of the discharge space, the field was measured at different points along the length and breadth of the pole pieces and was found to be uniform. The measured values of the magnetic field, in discharge space is entered in table 1. The signal from 1 kΩ resistor was connected to one of the channels and is seen as pulsation in the oscillogram. The origin of these pulsations (oscillation) is found to have shifted upward from the initial position set before the signal is applied. The shift indicates the presence of a residual current. It is measured by Singh and Shrivastava [9] as

$$\text{residual current}(I_r) = \frac{\text{shift (cm)} * \text{sensitivity (V cm}^{-1})}{\text{resistance}}.$$

Observations were made for initial currents of 100, 120 and 150 μA. The transverse magnetic field supplied by a calibrated electromagnet was used and the pressure inside the discharge tube was 0.427 torr. Keeping the pressure constant, the magnetic field was varied and the corresponding current, voltage across the discharge tube and residual current has been noted for values of magnetic field varying between 0 to 30 G. The process was repeated starting with different initial currents.

3. Results and discussion

The variation of average tube current and the corresponding voltage across the tube are plotted in figures 3 and 4 for initial tube current of 100 μA, 120 μA as two representative cases and data for 150 μA is entered in table 2. It is observed that the current decreases

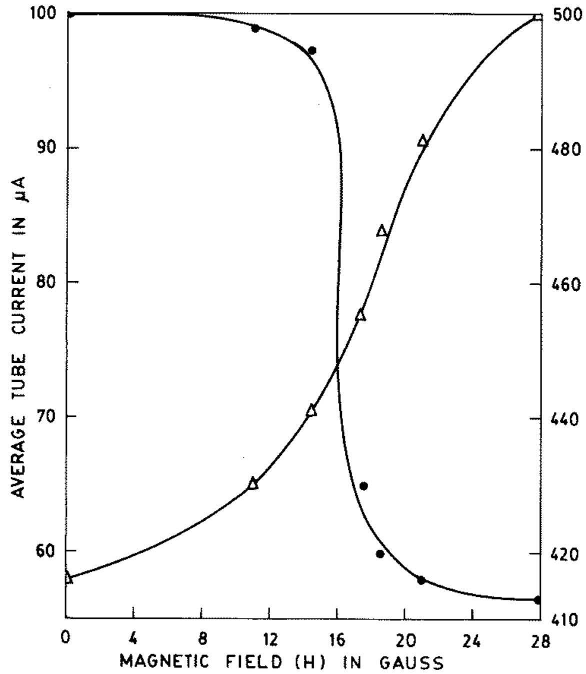

Figure 3. Variation of average tube current and axial voltage across the tube. Initial tube current 100 μA.

gradually with the increase of the magnetic field and the voltage across the tube increases. The residual current has also been computed and the variation of I_r against the magnetic field has been observed and plotted in figure 5 for different values of initial current. It is observed that the residual current decreases with the increase of the magnetic field. A simple explanation of the observed results can be given. The tube is excited by a d.c. source of voltage E_{dc} in series with a resistance R. In the absence of the magnetic field, the voltage drop across the tube $V_0 = E_{\mathrm{dc}} - IR$, where I is the initial current. Under the action of the transverse magnetic field, electrons are deviated from their straight line path and cannot contribute to the main current, which decreases. Hence, if V_H is the voltage drop across the tube in the presence of the magnetic field, $V_H - V_0 = R(I - I_H)$ and as I_H is less than I, so V_H will be greater than V_0 .

The effect of a transverse magnetic field on the positive column of a glow discharge has been investigated by Beckman [4]. He showed that the axial voltage increases in the presence of a magnetic field from E to $E[\alpha + \beta^2/\alpha]^{1/2}$, where

$$\alpha = 1 - h^2 + h^4 \exp h^2 \int_h^\alpha \frac{\exp(-h)}{h} \mathrm{d}h,$$

$$\beta = \frac{h}{2}\sqrt{\pi}\left[1 - 2h^2 + 4h^3 \exp h^2 \int_h^\alpha \exp(-h^2)\mathrm{d}h\right],$$

$$h = \frac{eH\lambda}{m\omega},$$

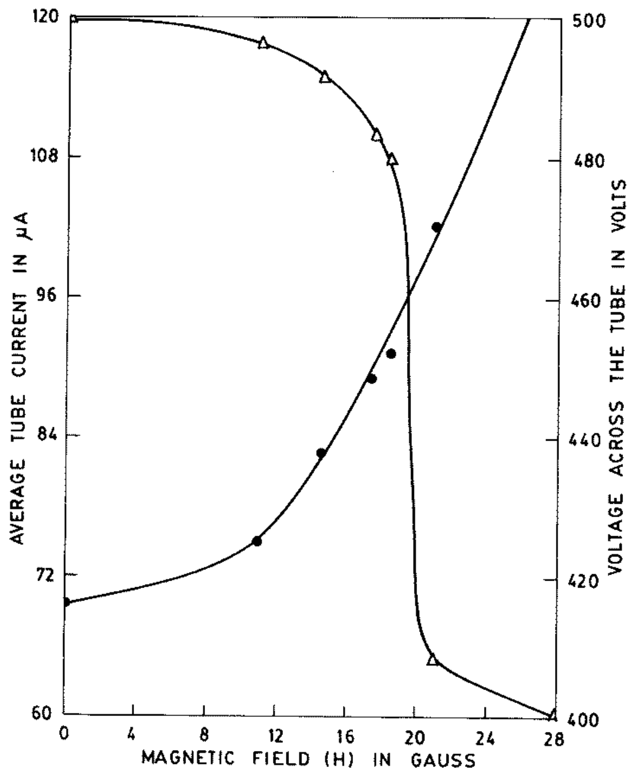

Figure 4. Variation of average tube current and axial voltage across the tube. Initial tube current 120 μA.

Table 2. Initial current 150 μA.

Magnetic field (G)	Average tube current (μA)	Voltage across the tube (V)
0	150	423
11.0	148	429
14.5	142	436
17.5	140	442
18.5	137	448
21.0	130	461
28.0	100	520

where H is the magnetic field, λ the mean free path, ω the most probable electronic speed. $\omega^2 = 2kT_e/m$ and,

$$h = 2eHh/mpv_r\sqrt{\pi}.$$

L is the m.f.p of the electron in the gas at a pressure of 1 torr,

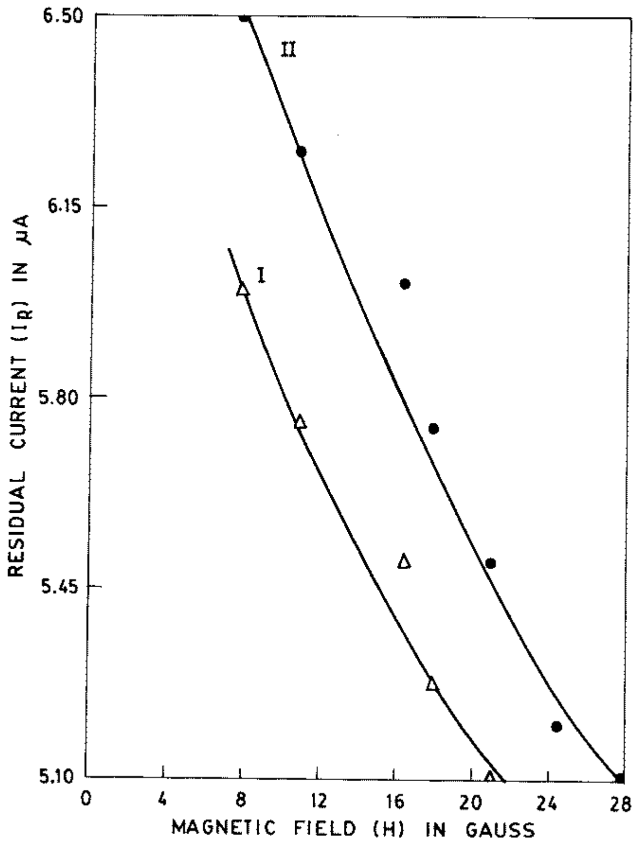

Figure 5. Variation of residual current with magnetic fields. Initial tube current (I) 90 μA, (II) 150 μA.

$$V_r = [8kT_e/m\pi]^{1/2}.$$

As h is small for the values of magnetic field used in the experiment,

$$\beta = \frac{h}{2}\sqrt{\pi} = \frac{eHL}{mv_r p} \quad \text{and} \quad \alpha = 1.$$

Hence

$$E_H = E[1+\beta^2]^{1/2} = E\left[1 + C_1\frac{H^2}{p^2}\right]^{1/2},$$

where C_1 is constant for a particular gas which is given by

$$C_1 = \left(\frac{e}{m}\,\frac{L}{v_r}\right)^2.$$

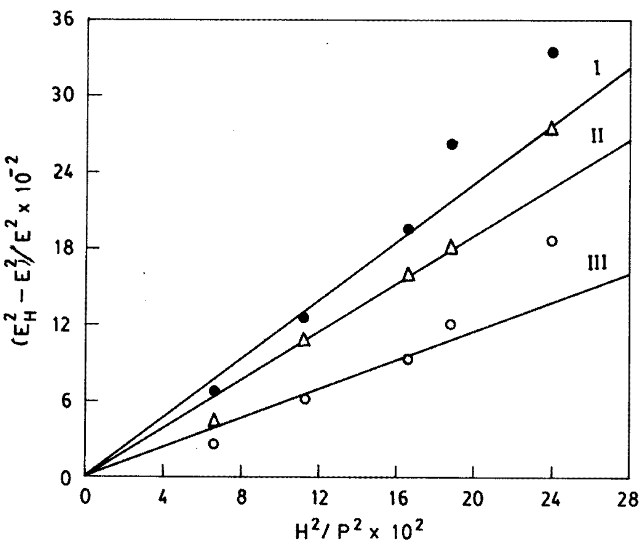

Figure 6. Variation of $(E_H^2 - E^2)/E^2$ against H^2/P^2. Initial tube current (I) 100 μA, (II) 120 μA, (III) 150 μA.

Table 3.

Initial current (μA)	C_1
100	$1.153 * 10^{-4}$
120	$1.000 * 10^{-4}$
150	$0.625 * 10^{-4}$

From eq. (2)

$$(E_H^2 - E^2)/E^2 = C_1 \frac{H^2}{p^2}.$$

As the pressure is kept constant, the variation of $(E_H^2 - E^2)/E^2$ against H^2/P^2 or against H^2 should be a straight line, and the slope of the curve should give the value of C_1. The variation has been plotted in figure 6 for all the initial discharge currents and the curves are straight lines passing through the origin, which shows that the derived equation

$$E_H = E\left(1 + C_1 \frac{H^2}{p^2}\right)^{1/2}$$

can represent to a fair degree of accuracy the variation of axial electric field with transverse magnetic field. It is evident from figure 6 that the points lie approximately on a straight line up to $H/P = 10^2$ G/torr and beyond this there is a gradual diversion from straight line behaviour. The value of C_1 as calculated from the curves for different initial currents has been entered in table 3. The value of C_1 can also be calculated from known values of L and v_r for air and is $0.152 * 10^{-4}$, which agrees at least in order of magnitude with the values obtained here. Further, if I_r is the residual current in the absence of the magnetic field then in the presence of the magnetic field,

$$\text{residual current } (I_{rH}) = \frac{\text{shift due to magnetic field (cm)} * \text{sensitivity (V cm}^{-1})}{\text{resistance}}$$

will decrease. In the subnormal glow region, the discharge consists of current pulses. These current pulses pass through the discharge tube in regular succession. During the passage of a current pulse there is a sudden increase in ionization of the gaseous medium. The ions and electrons thus created disappear soon after the pulse ceases; however, some ions and electrons still remain before the next pulse sets in. These remaining ions and electrons constitute the residual current. The presence of this current suggests that the discharge tube is not completely switched off between two successive pulses so far as the breakdown is concerned but a small amount of current always keeps flowing through it. At low average tube current, frequency of oscillations is low and the residual current is also low. At highest tube currents the frequency of oscillations increases, leaving a small time gap between successive pulses. This reduces the possibility of loss and the residual current thus increases with the increase in average tube current. The loss of ions and electrons between successive pulses can be attributed to processes such as ambipolar diffusion, volume recombination and attachment [10]. In the existing experimental conditions, ambipolar diffusion is likely to dominate. In the present study with transverse magnetic field the loss of ions is more prominent than that of electrons because the diffusion of ions is more than that of electrons and hence residual current with increasing transverse magnetic field decreases and also indicates the possibility of measuring the time needed for almost complete loss of ions and electrons created during the passage of a pulse. This may be possible by using a pulse generator of variable frequency as the source of excitation. It is expected that by decreasing the frequency of the pulse generator, the residual current will diminish. The frequency of the pulse generator corresponding to almost zero residual current can be used to find the characteristic loss time for ions and electrons under given experimental conditions.

4. Conclusion

It is observed that the discharge current decreases with increase of the transverse magnetic field and the results can be analytically explained by the Beckman theory. The values of C_1 can be calculated and it agrees with the value obtained from kinetic theory. A qualitative explanation has been provided for the variation of the residual current with the transverse magnetic field.

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