Pramāṇa, Vol. 11, No. 5, November 1978, pp. 661–671, © printed in India

Electron neutral collision frequency from breakdown measurements in crossed electric and magnetic fields

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MS received 5 May 1978; revised 21 August 1978

Abstract. A simplified method of determining the electron-neutral collision frequency at unit pressure ν_0 is presented in a number of gases (hydrogen, argon and air) in crossed electric and magnetic fields utilising the sparking voltage data and equivalent pressure concept. The values of ν_0 for low H/p are found to agree with those reported by other authors. But at high H/p, the estimated values of ν_0 are appreciably higher for all the three gases. The increase in the values of ν_0 possibly occurs due to the change of the electron energy distribution at higher H/p.

Keywords. Electron-neutral collisions; $(\mathbf{E}\times\mathbf{H})$ fields; sparking characteristics; equivalent pressure concept.

1. Introduction

The electron-neutral collision frequency ν, in the absence of a magnetic field, can be obtained in different gases (Brown 1959). In situations where a magnetic field H is applied perpendicular to the electric field E $(\mathbf{E}\times\mathbf{H})$, the electron motion across the magnetic field is hindered and this may have an effect on electron neutral collisions. In order to explain collision phenomenon in $(\mathbf{E}\times\mathbf{H})$ situations, Blevin and Haydon (1958) introduced the equivalent pressure concept (EPC) in which, on the application of a crossed magnetic field, an apparent increase of pressure is assumed due to reduction of the free path in the electric field direction. Using the EPC, Dargan and Heylen (1968) determined the electron-neutral collision frequency at unit pressure $\nu_0(\nu=\nu_0 p$, p is the gas pressure) in several gases. In their experiments the gas pressures were generally high ($p \geqslant 5$ torr). Since the influence of the magnetic field is expected to be more pronounced with the decrease of pressure, this study attempts to determine ν_0 at a comparatively lower pressure and to find out whether or not the transverse magnetic field has any influence on the values of ν_0.

To determine ν_0 utilising EPC and sparking voltage data, Dargan and Heylen (1968) obtained the following relationship at constant sparking voltage for zero and non-zero magnetic fields:

$$(pd)^2 + (pd)^2 \left[\frac{e}{m}\frac{H}{\nu}\right]^2 = (pd)_0^2. \quad (1)$$

Here d is the electrode separation, e and m the charge and mass of an electron respectively. The subscript zero refers to values of the parameters in the absence of H. For the above equality to hold, either d or p must decrease with the increase in H.

In order to obtain breakdown at a particular value of the potential, Dargan and Heylen (1968) varied d with H, keeping p constant. As pointed out by Haydon (1970), it is better to work with variable p rather than variable d. Moreover, if exact parallelism of the electrodes cannot be maintained while varying d, the electric field will be distorted. Furthermore, even if initial parallelism between the electrodes may be maintained during the variation, the degree of non-uniformity of the field will vary with varying d.

In the present study therefore, the pressure is varied while the electrode separation is kept fixed. It is hoped that this method would be an improvement over the previous ones besides being simple from the standpoint of experiment.

2. Theoretical considerations

To assess the effect of transverse magnetic field on the sparking voltage, the underlying theory is briefly examined. Using

(i) the criterion for breakdown for current instability (Townsend 1915)

$$\gamma\,\{\exp(\alpha d)-1\}=1; \tag{2}$$

(ii) an uniform electric field E

$$E=v/d; \tag{3}$$

(iii) the exponential dependence of (α/p) on E/p

$$(\alpha/p)=A\exp(-Bp/E); \tag{4}$$

the sparking potential in the absence of magnetic field V_{so} is given by

$$V_{so}=\frac{B(pd)_0}{\ln(pd)_0+\ln\left\{\dfrac{A}{\ln(1+1/\gamma)}\right\}}. \tag{5}$$

Here A and B are gas constants characteristic of the gas (Lewis 1958), α is Townsend's first ionisation coefficient and γ is the secondary ionisation coefficient. On applying a transverse magnetic field, the electron swarm is deflected through an angle θ. The sparking potential $V_{s,\,H/p}$ in the presence of the magnetic field is shown to be given by (Dargan and Heylen 1968):

$$V_{s,H/p}=\frac{B(pd\sec\theta)}{\ln(pd\sec\theta)+\ln\left\{\dfrac{A}{\ln(1+1/\gamma)}\right\}}. \tag{6}$$

Comparison of (5) and (6) reveals that for a fixed d, if the sparking potential is maintained constant with the increase in magnetic field, then

$$p_0 = p \sec \theta. \tag{7}$$

Assuming that the collision frequency is independent of the electron energy and Maxwellian energy distribution of electrons remaining unaffected in the presence of the magnetic field, Allis (1956) has shown that

$$\sec \theta = \left[1+\left(\frac{\omega}{\nu}\right)^2\right]^{1/2} = \left[1+\left(\frac{eH}{m\nu}\right)^2\right]^{1/2} \tag{8}$$

where $\omega = eH/m$ is the cyclotron frequency. Substituting (8) in (7), one obtains

$$p^2 + \left(\frac{e}{m\nu_0}\right)^2 H^2 = p_0^2. \tag{9}$$

From the slope of the plot of p^2 against H^2, ν_0 can be determined.

3. Experimental arrangement and procedure

The experimental arrangement is shown schematically in figure 1. The electrodes used are of aluminium 5 cm in diameter and separated by 5 cm. Gas pressure is indicated by thermocouple gauge (TG) and vacustat. The transverse magnetic field is produced by an electromagnet whose flux distribution between the pole pieces is homogeneous to within $\pm 1\%$.

The sparking condition is identified with the appearance of signals of a definite amplitude (2 mv) on the oscilloscope due to a current flowing through R_1 (figure 1). This condition for identification is maintained throughout the observation to ensure

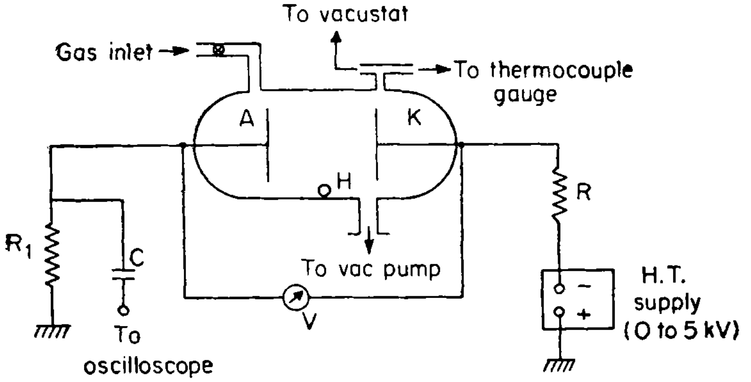

Figure 1. Schematic diagram of the experimental arrangement. Magnetic field is applied perpendicular to the plane of the paper as shown. $R = 100$ MΩ, $R_1 = 10$ KΩ, $C = 0{\cdot}01$ μF.

breakdown at a fixed current (2×10^{-7} amps). It corresponds to a Townsend discharge between the anode A and the cathode K. The potential difference across the discharge tube is identified as the sparking potential.

The following procedure is adopted. The gas is kept at a definite pressure and the sparking voltage in the absence of the magnetic field is determined. The transverse magnetic field is then applied, gradually increased in steps and the sparking potentials noted for selected values of H. The magnet is then demagnetised, pressure altered to some new value and the procedure repeated. This is done for all the three gases investigated yielding the sparking potentials of the gases at the various pressures.

The sparking characteristics with H as a parameter are drawn for hydrogen, argon and air and are shown in figures 2, 3 and 4 respectively. For each gas, horizontal lines parallel to the pressure axis corresponding to four different sparking potentials are drawn (e.g. figure 2). The intersections of each constant sparking potential line with the sparking characteristics (corresponding to various values of H) give the values of p corresponding to the values of H. The quantity p^2 is then plotted against H^2 for all the three gases as shown in figures 5, 6 and 7 for hydrogen, argon and air respectively. ν_0 is then estimated from the slope at three points on the curves, corresponding to three different values of the magnetic field.

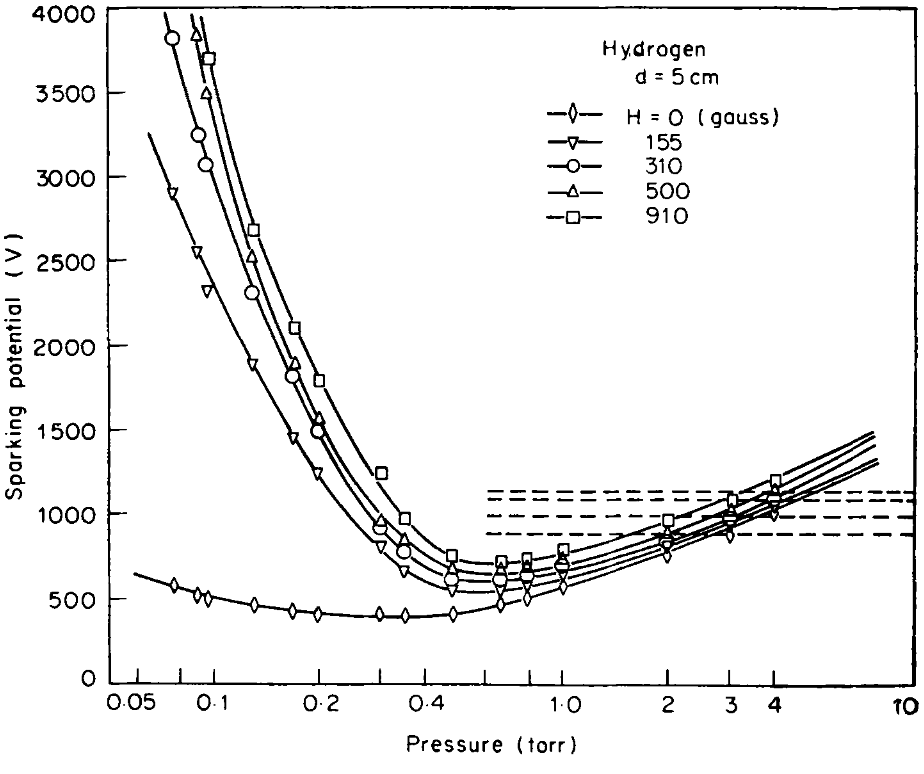

Figure 2. Sparking voltage characteristics for hydrogen, p is plotted in logarithm scale.

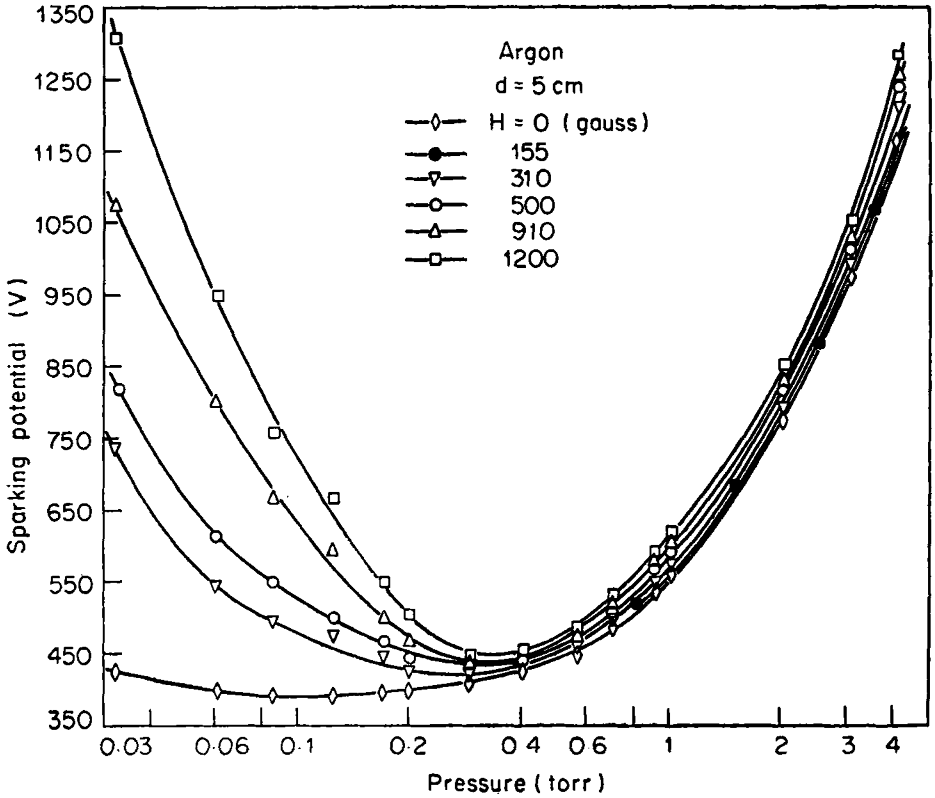

Figure 3. Sparking voltage characteristics for argon. p is plotted in logarithm scale.

4. Results

Dargan and Heylen (1968) reported a constant value of $\nu_0 = 3 \times 10^9$ (storr)$^{-1}$ for hydrogen for $30 < E/p < 110$. For argon they obtained $\nu_0 = 3{\cdot}5 \times 10^9$ (storr)$^{-1}$ at $E/p = 60$ V (cm torr)$^{-1}$. The estimated values of ν_0 as obtained in the present experiment are given in tables 1, 2 and 3 for hydrogen, argon and air, respectively. It can be seen from table 1 that for hydrogen, at low E/p and H/p, the estimated values of ν_0 are in fair agreement with the value $\nu_0 = 2{\cdot}5 \times 10^9$ (storr)$^{-1}$ reported by Fletcher and Haydon (1966) from conductivity measurements and also with those of Dargan and Heylen (1968). For argon (table 2) at $E/p = 60{\cdot}3$ V (cm torr)$^{-1}$ and $H/p = 27{\cdot}4$ gauss torr^{-1}, $\nu_0 = 4{\cdot}1 \times 10^9$ (storr)$^{-1}$, in agreement with Dargan and Heylen (1968). However, for hydrogen, even for $30 < E/p < 150$, ν_0 increases from $2{\cdot}3 \times 10^9$ (storr)$^{-1}$ at $H/p = 53{\cdot}7$ gauss torr^{-1} to $\nu_0 = 11{\cdot}1 \times 10^9$ (storr)$^{-1}$ at $H/p = 519{\cdot}8$ gauss torr^{-1}. The variation of ν_0 with H/p is also appreciable in the case of argon and air as is evident from tables 2 and 3 respectively.

5. Discussion

According to EPC, ν_0 should remain constant for a particular gas. The results of this study (§ 4) corroborate this for low H/p. But for high H/p, deviations from the

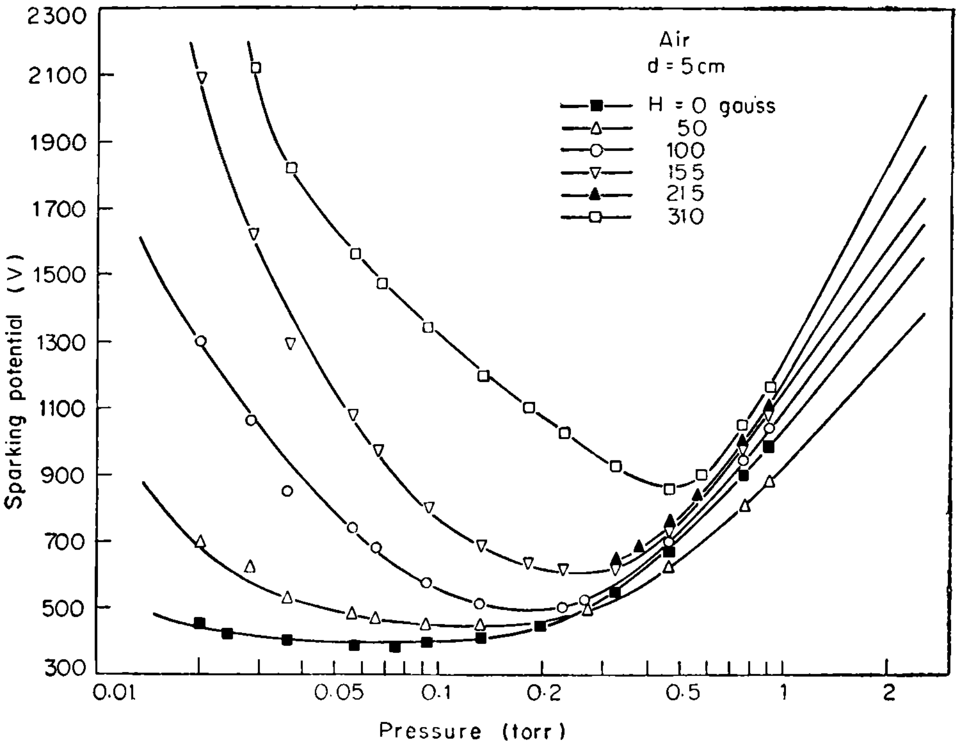

Figure 4. Sparking voltage characteristics for air. p is plotted in logarithm scale.

Table 1. Estimated values of collision frequency at unit pressure for hydrogen. ν_{OD} represents the estimated collision frequencies taking drift losses into account (Heylen and Bunting 1969). ν_0 as shown in the last column are those obtained from figure 5 of the present paper.

H (Gauss)	V_s (Volts)	p (torr)	H/p (Gauss torr^{-1})	E/p (Volt cm^{-1} torr^{-1})	tan θ $(=V_\perp\ V_T)$	$\nu_{OD}\times 10^{-9}$ (s torr)$^{-1}$	$\nu_0\times 10^{-9}$ (s torr)$^{-1}$
224	900	2·41	92·94	74·69	0·35	4·67	3·3
	1000	3·24	69·13	61·73	0·23	5·29	2·97
	1100	4·17	53·7	52·76	0·19	4·97	2·3
	1150	4·75	47·16	48·4	0·16	5·18	1·9
387	900	2·1	184·2	85·84	0·56	5·79	5·55
	1000	2·9	133·4	68·96	0·47	4·99	5·02
	1100	3·75	103·2	58·67	0·37	4·90	4·39
	1150	4·18	92·58	55·0	0·34	4·79	3·93
837	900	1·61	519·8	111·8	1·7	5·38	11·1
	1000	2·34	357·7	85·5	1·15	5·47	8·78
	1100	3·15	265·7	69·84	0·9	5·19	6·89
	1150	3·61	231·9	63·71	0·83	4·19	6·62

Table 2. Estimated values of ν_0 for argon as obtained from figure 6.

H (Gauss)	V_s (Volts)	p (torr)	H/p (Gauss torr^{-1})	E/p (V cm^{-1} torr^{-1})	$\nu_0 \times 10^{-9}$ (s torr)$^{-1}$
100	900	2·6	38·3	68·9	5·6
	1000	3·1	32·0	63·3	4·5
	1100	3·65	27·4	60·3	4·1
	1200	4·15	24·1	57·8	3·9
447	900	2·45	182·4	73·5	10·8
	1000	2·95	151·6	67·8	10·0
	1100	3·45	129·8	64·0	9·5
	1200	3·9	114·8	61·7	9·1
1100	900	2·3	482·5	78·9	26·7
	1000	2·8	395·8	71·9	24·6
	1100	3·25	338·6	67·7	16·9
	1200	3·7	301·0	65·7	15·7

Table 3. Estimated values of ν_0 for air as obtained from figure 7.

H (Gauss)	V_s (Volts)	p (torr)	H/p (Gauss torr^{-1})	E/p (V cm^{-1} torr^{-1})	$\nu_0 \times 10^{-9}$ (s torr)$^{-1}$
70	1000	0·9	79·5	227·3	5·1
	1100	1·05	67·3	211·5	3·9
	1200	1·25	56·0	192·0	2·9
	1300	1·5	47·3	179·8	2·5
122	1000	0·85	140·9	231·0	5·8
	1100	0·95	128·5	231·8	4·4
	1200	1·1	108·0	212·3	3·9
	1300	1·3	91·8	195·5	3·0
265	1000	0·7	368·1	277·7	13·0
	1100	0·8	316·4	262·9	13·8
	1200	0·98	270·4	244·9	11·1
	1300	1·1	140·9	236·6	8·1

constancy of ν_0 appear. The tables show that ν_0 has appreciably higher values at higher values of H/p for all the three gases considered. In order to ascertain the possible origin of the observed variation of ν_0 with H, analyses have been done for the different possible effects for the case of hydrogen. Hydrogen was chosen because numerous relevant data are available for this gas.

In finite electrode configuration, there is loss of particles due to $\mathbf{E} \times \mathbf{H}$ drift. This loss has been estimated in the present experiment for hydrogen. Heylen and Bunting (1969) assuming Maxwellian electron energy distribution calculated the electron transverse drift velocity V_T (in E direction) and the perpendicular drift velocity $V_\perp$ (perpendicular to both E and H) and their ratio $\tan\theta = V_\perp / V_T$ for moderate and strong magnetic fields. Figure 5 of their paper shows plots of $\tan\theta$ against E/p

with H/p as parameter. The values of tan θ appropriate in our cases have been approximately estimated from the figure. ν_{OD} in the presence of drift losses has then been estimated using eq. (8) of the present paper. This is shown in table 1. It is seen that ν_{OD} estimated by taking drift losses into account does not show appreciable variation while ν_0 estimated from our p^2 vs H^2 curves vary from $1{\cdot}9\times10^9$ (storr)$^{-1}$ to $11{\cdot}1\times10^9$ (storr)$^{-1}$. Thus the experimentally observed variation of ν_0 with magnetic field is not due to drift losses in finite electrode configuration.

Now, in order to interpret the observed increase of ν_0 with H/p one may argue that the influence of the metastables participating in ionisation may have an effect on the breakdown potentials. To apply EPC to such situations may not be appropriate (Haydon 1977). But in hydrogen which has no metastables, an effect similar to argon and air is observed. It appears therefore, that the metastable participation in ionisation cannot be the contributing factor to the observed variation.

The next possibility is that the energy distribution of the electrons gradually alters as the transverse magnetic field is increased. Haydon *et al* (1971) have shown from the solution of the Boltzmann equation that the energy distribution functions corresponding to zero (f_0) and non-zero magnetic field (f_B) are different and differ from the Maxwellian distribution (f_M) for the same mean energy. Taking the effect of the magnetic field on the electron energy into account, they have obtained values of ν (from pre-breakdown-ionisation measurements) greater than that would be obtained if the distribution is assumed to be unaffected by the magnetic field. The solutions of the Boltzmann equation (figure 1 of Haydon *et al* 1971) show that f_M is closer to f_0 than it is to f_B. For a particular gas pressure, the distribution of electron energy

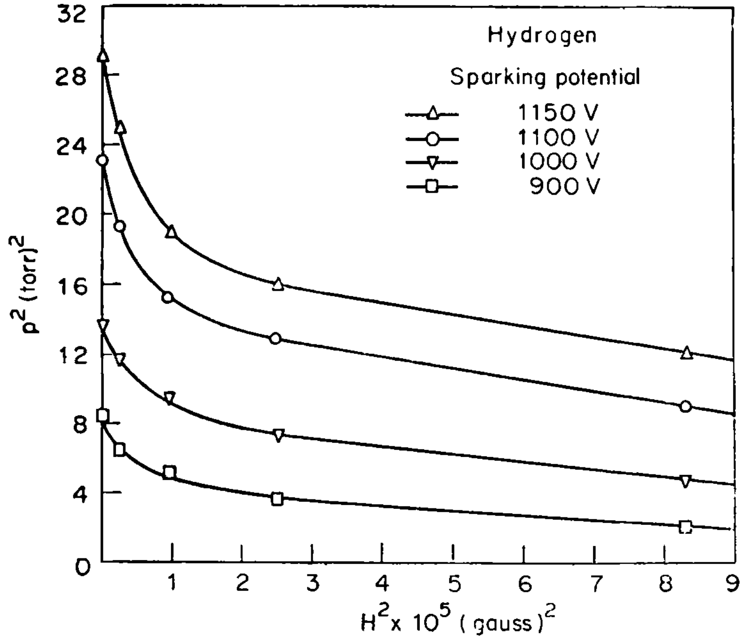

Figure 5. p^2 vs H^2 plots for hydrogen

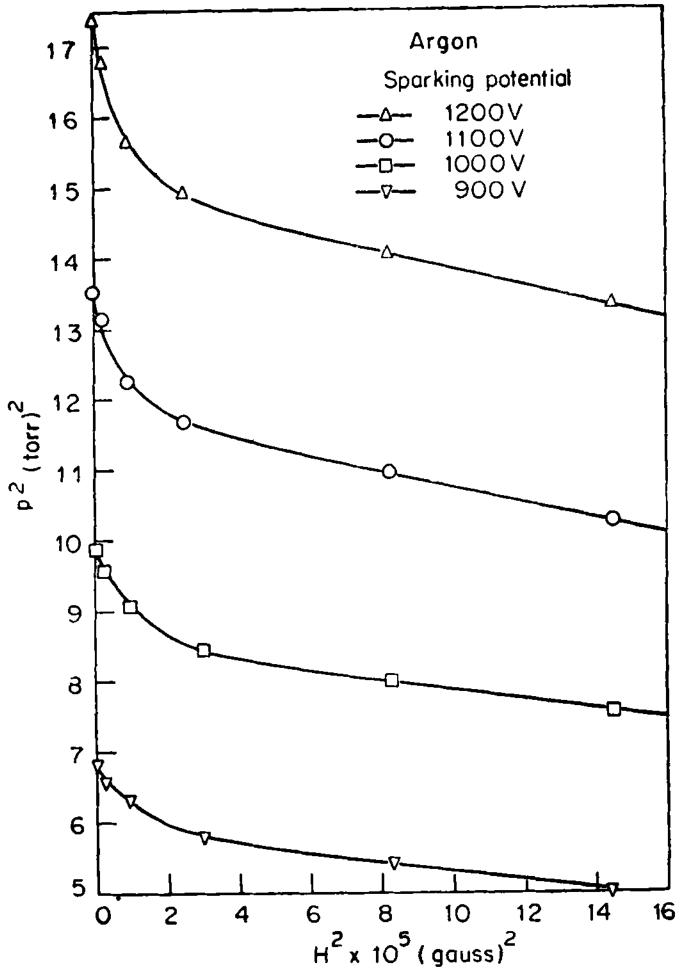

Figure 6. p^2 vs H^2 plots for argon

may be approximated by f_0 in the weak magnetic field limit. In this case EPC, with f_M as the distribution, can to a fair approximation, be applied. But at strong magnetic fields, a distribution like f_B is more appropriate, and under this condition EPC cannot be applied. So, the agreement in the present values of ν_0 at low H/p with the values obtained by other authors, and deviation thereafter can be explained in terms of the change of the electron energy distribution due to the transverse magnetic field.

There is however another important point which one should take into consideration. The theory of breakdown is valid for uniform electric field between the electrodes. In the present study, a tank plot indicated field non-uniformity $\leqslant 0{\cdot}05\,\%$ in the mid-plane upto 1·6 cm from the axis and about $\pm 5\,\%$ at the boundary. This non-uniformity remains the same throughout the observation since the electrode positions are not disturbed during the experiment (d constant). The field non-uniformity, therefore should not cause an increase in the values of ν_0 with increasing magnetic field.

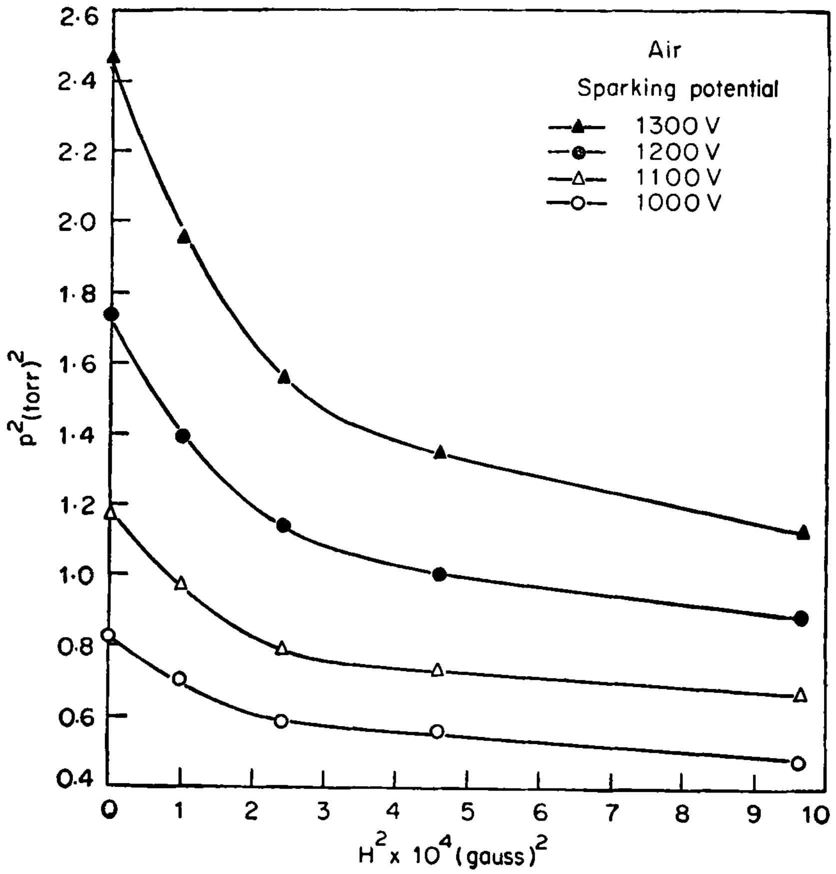

Figure 7. p^2 vs H^2 plots for air

6. Conclusion

The EPC applied in the original form (Blevin and Haydon 1958) for the determination of ν_0 has been found to be inadequate at comparatively stronger magnetic fields. From the experimental results it can be concluded that the transverse magnetic field does have an influence on the electron-neutral collision frequency at unit pressure measurements. This is thought to be due to the change in electron energy distribution under the action of the magnetic field.

Acknowledgements

The authors are indebted to Profs D N Kundu and S K Mukherjee for their interest in the work. They are also thankful to Mr S Banerjee for the technical assistance.

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