Combining the aforesaid equations we can derive the final expression for the number of ions produced along a cycloidal path. Since at B_c there is the discontinuity in the length of the electron path, this expression is separated into two ranges, depending on magnetic field:

1° for $B<B_c$

$$N_t=N_e n_g a\frac{d}{U_a}a\left\{\frac{2a^2+b-2c}{2(a^2+b-c)^{3/2}}\log\left[\frac{(\sqrt{a^2+b-c}+(\sqrt{a^2-c})^2}{b}\times\right.\right.$$

$$\left.\left.\times\frac{(\sqrt{a^2+b-c}-\sqrt{a^2-1})^2}{1+b-c}\right]\frac{b}{a^2+b-c}\left(\frac{\sqrt{a^2-c}}{b}\quad\frac{\sqrt{a^2-1}}{1+b-c}-\right)\right\};$$

2° for $B>B_c$

$$N_t=N_e n_g a\frac{d}{U_a}a\left\{\frac{2a^2+b-2c}{(a^2+b-c)^{3/2}}\log\frac{(\sqrt{a^2+b-c}+\sqrt{a^2-c})^2}{b}-2\frac{\sqrt{a^2-c}}{a^2+b-c}\right\},$$

where $a=B_c/B$, $b=\beta/U_a$, $c=U_t/U_a$, $B_c=\left(\frac{2m}{e}U_a\right)^{1/2}/d$.

The numerical example was calculated by digital computer for $U=300$ V and nitrogen (Fig. 1).

These calculations show that the gas ionisation was enhanced about four times and reaches the maximum at critical magnetic field, which was observed in many experiments$^{4)}$.

The above analysis is valid only for primary electrons. The complete analysis must take into account the ionisation processes caused by secondary electrons, as well as the influence of the space charge on the electron dynamics.

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3.31 Characteristic magnetic field in a gas magnetron diode

P. K. CIBIN and D. Đ. TOŠIĆ, *Institute of Nuclear Sciences "Boris Kidrič", Beograd, Yugoslavia*

The fundamental characteristic of the vacuum magnetron diode is the switching action of the magnetic field (cutoff). In the gas magnetron diode cutoff occurs at much higher magnetic fields, than in vacuum conditions, because the electron transport toward the anode is made possible owing to electron-neutral collisions. At over cutoff magnetic field the effective Larmor diameter of electrons is smaller than the anode radius, so the electron path lengthens many times, thus enabling the production of highly-ionized gas.

The aim of this paper is to explain an enhanced ionization in the gas magnetron diode below the cutoff, at low pressures.

Formulation of the problem

In the case when the magnetic field B is lower than critical magnetic field B_c (for cutoff), the emitted electrons reach the anode, so that their contribution in the gas ionization is relatively small. It is interesting to investigate what happens with secondary slow electrons generated in electron-neutral collisions. Since secondary electrons start from points in the interelectrode space, their potential energy is lower than eU_a, so there is possibility that they could not reach the anode. It means that the paths of those electrons are practically infinite, enabling thus an enhanced ionization. Evidently, there is minimum magnetic field (called characteristic magnetic field) at which the cutoff of secondary electrons appears.

The starting relation is the condition for the cutoff of the secondary electrons, which have zero initial velocity at some radius $r=r_0$,

$$U_a - U_{r_0} = \frac{e}{8m} B^2 R_a^2 (1 - r_0^2/R_a^2), \tag{1}$$

where U_a is anode voltage, U_{r_0} potential at the radius r_0 (with respect to the cathode), R_a anode radius[1)].

For the primary electrons ($r_0=r_k$, $U_{r_0}=0$), Eq. (1) gives

$$U_a = \frac{e}{8m} B_c^2 R_a^2 (1 - r_k^2/R_a^2), \tag{2}$$

which is the cutoff condition.

Results

Neglecting space charge effects, there is the logarithmic potential distribution in the cylindical magnetron diode, so the Eqs. (1) and (2) can be combined to yield

$$\frac{\log \dfrac{R_a}{r_0}}{(1 - r_0^2/R_a^2)^2} = \frac{B^2}{B_c^2} \frac{\log \dfrac{R_a}{r_k}}{(1 - r_k^2/R_a^2)^2}. \tag{3}$$

which is, in fact, the equation with two variables r_0 and B.

To obtain the minimum magnetic field, for which the condition (3) is satisfied, we equate to zero the derivative of the left hand side of Eq. (3). This gives the numerical equation

$$4 \log \frac{R_a^2}{r_0} - \frac{R_a^2}{r_0^2} + 1 = 0 \;\Rightarrow\; r_0 = r_0^* = 0.534\, R_a. \tag{4}$$

Substituting r_0^* in (3) we obtain the characteristic magnetic field

$$B^* = 1.108\, B_c \frac{1 - r_k^2/R_a^2}{\left(\log \dfrac{R_a}{r_k}\right)^{1/2}}. \tag{5}$$

Naturally, the characteristic magnetic field B^* must be lower than B_c. This condition is satisfied only if $r_k/R_a < 0.534$.

In our experiments[2] we used the magnetron diode with $R_a = 17.5$ mm and $r_0 = 0.5$ mm, so the ionization phenomena increase at $B^* = 0.587\, B_c$.

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3.32 Proposed laser application of the gas magnetron discharge

V. I. MILJEVIĆ, *Institute of Nuclear Sciences "Boris Kidrič", Beograd, Yugoslavia*

The behaviour of ionized gas in the cylindrical magnetron diode strongly depends on the intensity of the axial magnetic field. Between collisions the electrons move along cycloidal paths around the cathode, leading to an increase of the collision probability. Thus there is an effective shortening of the electron mean free path, which can be attributed to an apparent increase of the gas pressure. When the magnetic field reaches the critical value $B = B_{cg} >> B_c$, the arc current is cut off, where B_c is the well known cutoff magnetic field for the vacuum case $B_c = (8\, m U_a/e)^{1/2}/R$ (U_a -anode voltage, R-anode radius).

Spectroscopic investigations were undertaken to get more insight in the state of the ionized gas within the diode[1]. Spectra were registered in a hot cathode magnetron diode, filled with argon, operated in stationary and pulsed regimes, along and across the lines of the magnetic field. Working conditions of a stationary regime were: the anode voltage up to 150 V, the anode current up to 10 A. In the pulsed regime a condenser bank (5 μF, 800 V) was discharged through the magnetron diode. In both cases the cathode heating current was up to 55 A and magnetic field up to 1 kG.

It was found that the spectrum at $B > B_c$ contains only ion lines of argon AII, while atomic spectral lines were not registered, not even with very prolonged exposures. Those results were obtained in a wide pressure region, of the order of