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IONIZATION WAVES IN THE MEDIUM PRESSURE HELIUM AND NEON PLASMA

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We present the experimental results obtained on the ionisation waves in the helium and neon plasmas, within the pressure range of 200 Pa to 2000 Pa (133 Pa = 1 Torr), and for discharge electric currents of 5 mA to 35 mA. The main characteristics of the ionization waves in the medium presure neon and helium discharge are a small amplitude and a high frequency. The amplitude of the waves is smaller than 1 V. In the case of the neon plasma, the frequency varies between approximately 700 Hz and 2250 Hz and increases with the discharge current. In the helium plasma, the frequency is in the range between approximately 1500 Hz and 4000 Hz and decreases with the discharge electric current.

1. Introduction

The simplest condition of discharge in a gas is when the positive column is homogeneus and the discharge current is constant. Such a condition can not be always provided. Many studies have been dedicated to the oscillations which take place during the electrical discharges in gases. A special interest was paid to the moving and standing striations of the positive column, with impressive displays. Many measurementrs were made, but a complete theoretical explanation is still lacking.

Pekarek [1] has introduced the term ionization waves for the moving striations, emphasizing their basic nature. Pupp [2] has shown that moving striations in pure rare gases at constant pressures do not occur above a certain critical current which can be expressed by the empirical relationship:

$$I_c = C/p^{\gamma}, \tag{1}$$

where p is the pressure, and C and γ are constants that differ from gas to gas.

A theoretical relation for the upper limiting disharge current has been derived by Alankyan and Mikhalev [3], who obtained:

$$(I_c p)^2 = AI_c p\left(\frac{E}{p}\right) + B(p\Lambda)^2, \tag{2}$$

where $\Lambda = \sqrt{D_a \tau}$ is the diffusion length, τ is the time constant for the ions to diffuse to the tube wall, and A and B are constants depending on the gas and electron temperature. The first term from the right-hand side of the Eq. (2) is dominant at low pressure while the second term is dominant at high pressure. The ionization waves may be both self-excited or stimulated from outside and are further distinguished by their velocities and their $E\lambda$ product, where E is the axial electric field and λ the wavelength of the waves [4].

Four varieties of waves have been experimentally observed, two slow types (called p and s') and two fast types (called r and s). The p-wave arises due to oscillations of the metastable density, while the dominant processes of the r-waves are the oscillations of the ion density. The s and s' waves are associated with molecular ions and with their formation caused by the collisions of excited atoms.

We present the results obtained in measurements of the self-excited ionization waves of p-type obtained in medium pressure helium and neon discharge plasma.

2. Theoretical considerations

The first mathematical model and consequently some of the most important advances in the theory of the ionization waves is that of Pekarek and Krejici [5]. Their model was based on four linear equations for the ions and electrons, the Poisson's equation and the energy equation for electrons. They obtained an integro-differential equation for striations which can be solved in some simplified cases. Several methods, like the numerical evaluation [6], the Fourier expansion [7] and the Laplace-transform [8] have been applied to solve this set of equations.

The most realistic analysis for ionization waves near the Pupp limit was performed by Wojaczeck [9]. He used a complete expression for the electron energy equation, including thermal conductivity and diffusion due to the electron temperature gradients. Later, some research groups [10-12] have reported different models based on the Van der Pool oscillator-like model for driven ionization waves.

For our experiment, the basic equations are [13]:

$$\frac{\mathrm{d}n_i}{\mathrm{d}t} + n_i \nabla \cdot \vec{v}_i = s$$

$$\frac{\mathrm{d}\vec{v}_i}{\mathrm{d}t} + \nu_i \vec{v}_i - \frac{q}{M}\vec{E} = 0$$

$$-\nabla \cdot (n_e \vec{v}_e) = s \tag{3}$$

$$k\nabla(n_e T_e) + q n_e \vec{E} + \nu_e m \vec{v}_e n_e = 0$$

where n_i, is the ion density, n_e the electron density, v_i the ion drift velocity, v_e the electron drift velocity, k the Boltzmann constant, q the elementary charge and s the source term.

The relation between the field and the electron temperature is [5]:

$$\frac{\partial T_e}{\partial z} = aT_e - bE \tag{4}$$

where T_e is the electron temperature, a and b constants and z the axial coordinate. Then the dependence of the time variation of the ion density n_i is approximately given by [14]:

$$\frac{\mathrm{d}^2 n_i}{\mathrm{d}t^2} - (\alpha_0 - 2\beta n_i - 3\gamma n_i^2)\frac{\mathrm{d}n_i}{\mathrm{d}t} + \omega^2 n + C_1 n^2 + C_2 n^3 = 0 \tag{5}$$

where $\alpha_0 = \alpha - v_i$ is the effective linear growth rate, ν_i the collision frequency between ions and neutral atoms, β and γ are constants, ω is the wave pulsation and

$$C_1 \approx \beta\left[\nu_i + \nu_e\left(\frac{m}{M}\right)\right], \quad \text{and} \quad C_2 \approx \gamma\left[\nu_i + \nu_e\left(\frac{m}{M}\right)\right],$$

where m is the electron mass, M the ion mass and ν_e the collision frequency between electrons and neutral atoms.

Finally, ω is expressed by

$$\omega = ka^2\left(\frac{q}{q-kb}\right)^2 \sqrt{\frac{bT_e}{M(q-kb)}}\frac{1}{K}, \tag{6}$$

where K is the wave number. Equation (6) is regarded as a dispersion relation of the ionization wave, which has a backward-wave characteristic. Here, a is about 10 m^{-1} and b about 5×10^3 KV^{-1} in the case of neon, and a is about 2.5 m^{-1} and b about 10^4 KV^{-1} in the case of helium.

From the theory of Novak [4], the product $E \cdot \lambda$ is a constant for a gas of about 9.3 and 14.2 V in the case of neon and helium, respectively.

3. Experiment

The experimental set-up is shown in Fig. 1. The steady-state plasma was formed in the cylindrically-symmetric positive column in a 40 cm long and 4.5 cm inside-diameter glass tube. The electrodes were made of nickel and had a Rogowsky profile. The connections between each electrode and metal-to-glass seals are made of a metal piece and a helical wire, and the distance between the electrodes could be varied from 20 to 40 cm by means of magnetic coils. Three wolfram probes with glass insulation, S_1,S_2 and S_3, having a diameter of 1.5 mm, were placed within the discharge gap. Another identical probe, S_4, was placed opposite to the probe S_2. The probes have plain tips. The radial position of the probes could be varied (also by means of magnetic coils), so the probes S_2 and S_4 could be put in contact.

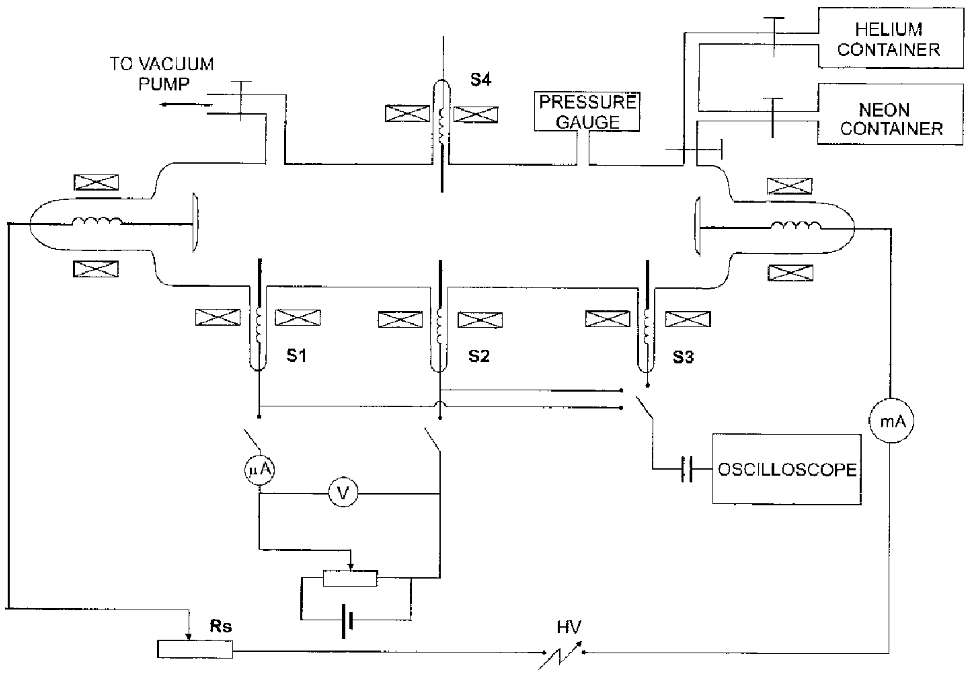

Fig. 1. Experimental set-up.

The discharge tube was connected to the vacuum system, degassed and filled with spectroscopically pure helium or neon gas, close to the value of the medium working pressure.

The working range of the electric discharge current was from 1 to 35 mA. To observe the self-excited ionization waves in the plasma, we used an electric method which allowed the recording on the oscilloscope of both the wave frequency and the plasma potential amplitude via the electrostatic probes.

The DC supply source (RFT-STARTON 4205 type, max. 1.5 kV and 0.2 Amperes) had 50 Hz pulses superimposed on the constant component of the voltage. This caused a modulation of the electric signal from the probes. Using a supply source with a long time constant, we could sustain the glow discharge even after the disconnection of the source, which allowed the modulated signal to be seen on the oscilloscope. The axial electric field was determined by the double-floating-probe method.

The discharge in neon was studied at pressures of about 200, 530, 930, 1330, 1600 and 2000, and in helium at pressures of about 670, 930, 1460 and 1860 Pa Pa (133 Pa = 1 Torr). The discharge current was in the range of 1 mA to 35 mA. Both the amplitude and the frequency have been recorded. The electric signal from the positive column (the probe S_1 in the area of the anode and the probe S_2 at the head of the positive column) as well as the negative glow (the probe S_3 in the area of the cathode) were measured.

TABLE 1. The results of measurements of the frequency and amplitude of oscillations, and the calculated frequencies, in neon plasma for different values of the discharge current (I) and of the product pressure times radius, pR ($R = 2.25$ cm).

I (mA)	$R \cdot p$ (cmPa)	E/p ((mV/cm)/Pa)	ν_{osc} (Hz)		V_{osc} (V)		v_g^{calc} (m/s)	ν_{osc}^{calc} (Hz)
			S_1	S_2	S_1	S_2		
5	500	6.01	440	450	0.3	0.2	36.67	475
	1300	3.38	1200	1000	0.4	0.3		710
	2300	2.66	1250	1125	0.5	0.4		980
	3300	3.44	1250	1500	0.5	0.4		1805
	4000	2.17	2000	2250	0.6	0.5		1365
	5000	2.74	2250	2000	0.6	0.5		2160
15	500	5.64	750	650	0.15	0.2	40.54	490
	1300	3.16	1000	1000	0.30	0.3		730
	2300	2.59	1250	1200	0.50	0.4		1055
	3300	3.57	1500	1500	0.60	0.5		1950
	4000	2.08	1250	1750	0.60	0.5		1450
	5000	1.93	1300	1500	0.70	0.6		1680
25	500	5.34	900	900	0.15	0.1	51.13	585
	1300	3.31	1000	1250	0.30	0.2		880
	2300	1.95	1250	1250	0.50	0.4		1000
	3300	2.52	1500	1750	0.60	0.4		1840
	4000	1.83	2000	1800	0.60	0.5		1605
	5000	1.45	1700	1750	0.60	0.5		1590
35	500	5.26	1000	900	0.1	0.1	74.97	845
	1300	2.86	1200	1250	0.3	0.2		1225
	2300	1.29	1250	1250	0.5	0.4		970
	3300	1.68	1750	1500	0.6	0.5		1805
	4000	1.25	1750	1800	0.6	0.6		1610
	5000	1.17	1700	1750	0.6	0.6		1890

4. Results

In all situations, the plasma column had a single-source appearance, but the electric signal recorded via the electrostatic probes evinced the presence of the p-type self-excited waves. For the neon plasma, at medium and low pressure, the results for the recorded signals are shown in Table 1.

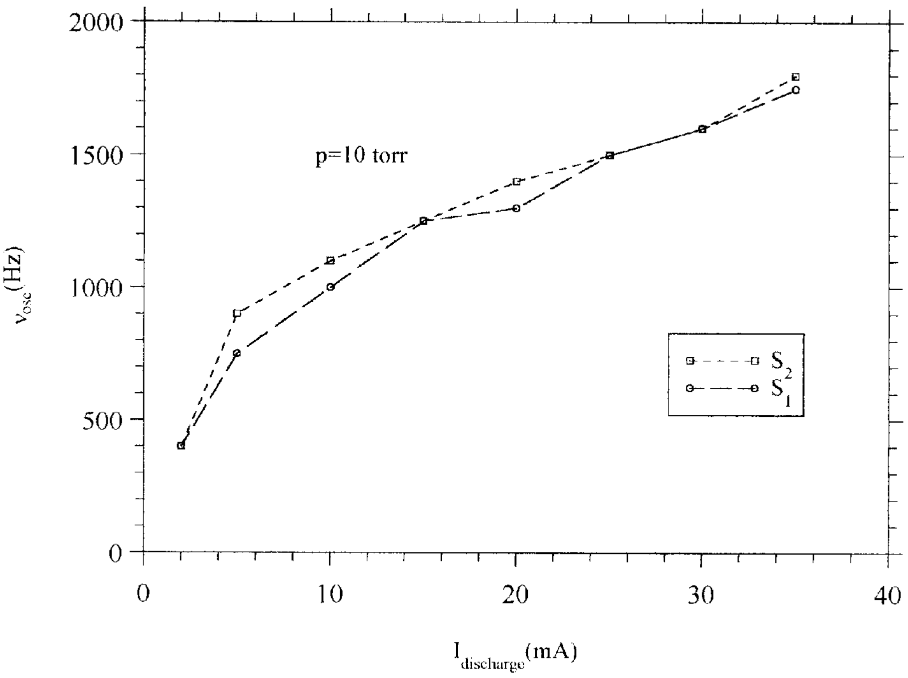

Fig. 2. The dependence of frequency vs. the current at p = 1330 Pa *for the probes S_1 and S_2. (133* Pa = *1* Torr.*)*

Figure 2 shows the dependence of the wave frequency on the electrical discharge current for the neon plasma. Essentially, there is no difference between the low and the medium pressure ionization waves, both being of the same physical nature. Only differences of the slopes of the curves are seen for the same values of the electrical discharge current but at different values of the pressures. The frequency increases with the increase of the discharge current.

In the case of the helium plasma, essential differences were observed. The results are shown in Table 2. The wave frequency decreases when the electrical discharge current increases and, for the same value of the electrical discharge current, the wave frequency is greater for discharge in helium.

The differences between discharge in neon and in helium are due to the jumping phenomena [15]. They are present in the case of neon: the frequency suddenly jumps to a higher value with an increase of the current, and the discharge reverses suddenly back to the previous state.

TABLE 2. The results of measurements of the frequency and amplitude of oscillations, and the calculated frequencies, in helium plasma for different values of the discharge current (I) and of the product pressure times radius, pR (R = 2.25 cm).

I (mA)	$R \cdot p$ (cmPa)	E/p ((mV/cm)/Pa)	ν_{osc} (Hz)		V_{osc} (V)		v_g^{calc} (m/s)	ν_{osc}^{calc} (Hz)
			S_1	S_2	S_1	S_2		
5	1500	6.99	3000	3000	0.4	0.3	54.63	1795
	2100	5.57	2250	2500	0.5	0.3		2000
	3300	5.22	3000	3000	0.5	0.4		2945
	4200	6.43	2900	3000	0.5	0.4		4620
15	1500	7.01	3300	3300	0.6	0.3	50.44	1660
	2100	5.81	2000	2000	0.8	0.5		1925
	3300	5.27	2000	2000	0.8	0.5		2750
	4200	6.50	1900	1800	1.0	0.6		4310
25	1500	8.63	2500	2250	0.5	0.4	39.37	1595
	2100	6.32	2000	2000	0.8	0.7		1635
	3300	5.42	2100	2000	1.0	0.8		2205
	4200	6.69	1700	1800	1.2	0.8		3465
35	1500	10.32	4000	4000	0.6	0.4	32.18	1560
	2100	6.35	2000	2000	0.8	0.8		1340
	3300	6.02	1800	1800	1.0	0.8		2000
	4200	7.40	1500	1750	1.2	1.0		3135

In the neon plasma, there is an instability onset of the ionization waves corresponding to a certain value of the discharge current. As can be seen from the Tables 1 and 2, the dependence of the ionization wave frequency on pressure is different in the case of the helium plasma and the neon plasma.

Within the margins of the experimental errors, no essential differences between the frequencies recorded with the probes S_1, S_2 and S_3 for the same values of the gas pressure and the electrical discharge currents have been noticed. By putting in contact the probes S_2 and S_4, the frequencies of the signals from the probes S_1 and S_3 were not altered. The small differences between the measured and calculated frequencies seem to appear because of the dependence of the frequency on the tube radius which is not included in our theoretical model.

5. Conclusions

In the case of neon plasma, the basic characteristics of the waves are the low amplitude (less than 1 V) and the high frequency (between 700 Hz - 2500 Hz). This is to be compared with the ionization waves from the neon glow discharge at low pressure which had a high amplitude and a low frequency.

For helium plasma, the wave amplitudes are also low, but the frequencies are higher by a factor of two than in the case of neon.

In case of the neon plasma our results are a little different from the theoretical and experimental results of Pekarek's group [16]. They observed a frequency of the same order of magnitude (1000 Hz), but they worked at a lower pressure (200 Pa) and used a tube of a smaller diameter (8 mm).

The results of Ohe and Tekeda [17] for both the case of neon plasma and helium plasma are greater than our results by one order of magnitude. They worked at a lower pressure and their tube diameter was between 4 and 8 mm.

For practical applications, in majority of cases, due to the low value of the amplitudes of ionization waves at medium pressure, these waves can be neglected.

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IONIZACIJSKI VALOVI U NEONSKOJ I HELIJEVOJ PLAZMI NA OSREDNJEM TLAKU

Proučavali se se ionizacijski valovi u neonskoj i helijevoj plazmi za tlakove između 200 i 2000 Pa i pri izbojnim strujama od 5 do 35 mA. Amplitude oscilacija su male a frekvencije visoke. U neonskoj plazmi frekvencija je od 450 do 2250 Hz i raste sa strujom, a u helijevoj između 1750 i 4000 Hz i smanjuje se s povećavanjem izbojne struje.