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Radiation from Hot Plasma of High-Pressure Discharge in Magnetic Field

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Abstract. We have considered the effect of the bulk energy density on the formation of a high-current discharge plasma in Ar (P = 2280 Torr) in the presence of preionization and the application of longitudinal magnetic field. The formation of the initial stages of a high-current discharge changes with increasing bulk density of energy, switching from a continuous form to the brightness pulsation. We have detected that the external critical magnetic field accelerates the process of formation of all stages of the discharge with a simultaneous increase in the maximum of the bulk density of energy, concentration, and temperature. It should be specially noted that the appearance of new spectral lines at the stage of the spark channel formation in an external longitudinal magnetic field.

1. Introduction

The spark channel of a high-current discharge in high-pressure gases possesses considerable brightness. An external critical magnetic field, creating an ordered structure and limiting the transverse expansion of the discharge plasma, leads to a directed increase in the radiated energy. To apply a spark as a source of radiation with tunable frequency and with a maximum of spectral density in the ultraviolet region, it is necessary to determine the physical conditions for the formation of discharge plasma in a critical magnetic field [1-4]. By increasing the rate of input and the value of the specific energy in the spark channel plasma in an external magnetic field, the conductivity and temperature of the plasma can be greatly increased. Our experiments have shown that the spectral composition of the radiation and the intensity of the continuum depend on the strength of the external longitudinal magnetic field $H$. The continuous radiation intensity maximum shifts to the short-wave region with a simultaneous increase in the temperature $T_e$ and electron concentration $n_e$.

2. Experiment

The experimental setup was assembled from two independent electrical circuits – a pulse magnetic field generator (PMFG) and a pulse voltage generator (PVG) – operating synchronously with a synchronization unit.

The additional spark discharge ultraviolet source was located at a distance of 5-7 cm from the main discharge gap axis. In this position, the illumination spark makes it possible to form in one case – an equal axis concentration of seed electrons, and in the other case – the same concentration over the cross section. For the formation of UV-ionization, we’ve used the thyratron system TGI1-400/16.
The external magnetic field was created due to the discharge of the capacitor bank through the solenoid, within which the studied gap was located. The parameters of the capacitive storage-solenoid system were chosen according to the requirements for ensuring the quasistationary nature of the external magnetic field (the period of the magnetic field up to 500 kOe is 600 μs, and the duration of the electric field voltage pulse is up to 1 μs). The design of the solenoid and its type was chosen based on the required magnitude of the magnetic field, mechanical strength, and simplicity of construction. The discharge radiation was registered through the side openings in the central coil of a solenoid (1 cm thick), which was an all-metal construction of beryllium bronze with a number of turns of 33, an inner diameter of 8 mm, and an inductance of $L_0 = 5 \times 10^{-6}$ H.

To study the spectra of a high-current high-pressure discharge in inert gases (Ar, He) in the transverse and longitudinal directions of discharge development we have used a radiation spectra mechanical scanning, the temporal resolution of which is up to 10 ns. The Stark broadening and the relative intensity of the spectral lines were used to calculate the electron concentration and temperature in high-current discharge plasma.

The spectral distribution of the plasma radiation of the discharge different stages depends on the intensity of the external magnetic field, the degree of influence of which is determined by the limitation of the radial diffusion of charged particles and the rate of expansion of the spark channel.

The spectrum was recorded using a quartz spectrograph ISP-30 coupled with a high-speed photographic recorder VFU-1, and the intensity of individual spectral lines was registered by a double monochromator DMP-4 in combination with photoelectric multipliers FEU-29 and FEU-79. The technique and the optical scheme explaining the principle of synchronizing the recording of the spectrum with the electric discharge parameters are described in [5] The emission spectra of the emerging spark discharge in Ar and He have a sufficient intensity, so they are clearly recorded on the photographic film at discharge currents of 40-50 A. The spectra were recorded under conditions of a linear dependence of the optical density of the photographic film on the illumination, with numerical modeling based on the computer program Mathcad.

### 3. Results and discussion

The experimental data analysis shows that the application of an external longitudinal magnetic field leads to a change in the radiation intensity, both in time and in wavelengths. The radiation intensity in the short-wave region of the spectrum increases earlier due to the magnetic field superposition, and for the long-wavelength region of the spectrum, a later increase in the radiation intensity is characteristic with an increase in the strength of the external longitudinal magnetic field.

Integral spectra of longitudinal radiation in the breakdown of Ar are shown in Fig. 1 in an external magnetic field ($H = 400$ kOe) and without it ($H = 0$) for $P = 2280$ Torr, $d = 0.3$ cm. As the experimental results have shown, an external longitudinal critical magnetic field, creating an ordered structure in the gas and accelerating the process of formation of all stages of the discharge leads to an increase in the luminescence intensity.

The spectrograms of the emission of the spectral region during breakdown in Ar for $H = 0$ and 400 kOe are presented in the Fig. 2. We have indicated within the framework the wavelengths of the spectral lines ($λ = 330.2$ nm, Zn), which appear at the stage of the development of the spark channel (120 ns) and ($λ = 269.76$ nm, Rh, Os), which appear at the stage of combustion of a quasistationary arc (200 ns) at $H = 400$ kOe and doesn’t appear in the zero field.

In a strong longitudinal magnetic field, the atoms of inert gases are magnetized. Their magnetic susceptibility $\chi$ is independent of temperature, and the magnetization vector is proportional to the value of this field strength. We assume that an ordered structure is created before the breakdown impulse of the electric voltage is applied. Note that the magnetic fields act for 600 microseconds, and the electric field pulse is 1 microsecond; in fact, the gas and plasma are in a strong magnetic field, which creates anisotropy of radiation along the lines of force of the magnetic field, which in our opinion can lead to an increase in directional radiation from the plasma of the gas discharge.

Spectral measurements make it possible to estimate the electron temperature $T_e$ and the concentration $n_e$ for avalanche-streamer transitions.
Figure 1. (color on-line). Integral emission spectra of a discharge in Ar along the external longitudinal magnetic field force lines. $P = 2280$ Torr, $d = 0.3$ cm; $U_{br} = 6$ kV; $U_{stat} = 4.7$ kV.

Figure 2 (color on-line). The sequence of emission spectra of Ar ($d = 0.3$ cm, $P = 2280$ Torr, $U_{br} = 5$ kV in the range 250 nm-550 nm, solid line - $H = 0$; dotted - $H = 400$ kOe).

To determine the temperature of the plasma of the spark channel we have used the method of relative intensities of the spectral lines. This method is based on the fact that for plasma in the state of partial local thermodynamic equilibrium (PLTE) the ratio of line intensities is:
\[
\frac{I_1}{I_2} = \frac{f_1 g_1 \lambda_1^2}{f_2 g_2 \lambda_2^2} \cdot \exp \left( -\frac{E_1 - E_2}{kT_e} \right).
\] (1)

Here \( f_1 \) is the line oscillator strength of the wavelength \( \lambda_1 \), \( E_1 \) is the excitation energy, \( g_1 \) is the ratio of the static weights of the upper and lower levels. For the line \( \lambda_2 \) the corresponding parameters are indicated by the index "2". Eqn. (1) is used for lines of the same ionization multiplicity.

There are certain requirements that spectral lines used to calculate temperature must satisfy: the parameters of these lines must be known, there should be no self-absorption, etc. In our case, the most convenient are the lines ArII-448.18; 454.5; 480.6; 476.4; 484.7 nm. First, these lines are quite bright in the emission spectrum of the channels, and secondly, the parameters [6] entering into (1) are tabulated for these lines. For most lines of argon ions, distortion of the line profile due to self-absorption is small [7-9]. For the line 480.6 nm at \( n_e \sim 10^{18} \text{ cm}^{-3} \) and \( kT_e = 3 \text{ eV} \) the optical thickness is 1 cm, which is much larger than the characteristic channel size. Testing the self-absorption of lines by combining each point of the emitting volume with its image also showed that the plasma in the lines can be considered transparent. The parameters of optical line transitions for the temperature calculating are given in the Table 1.

| No | \( \lambda \), nm | \( E_1 \), J | \( E_2 \), J | \( g_1 \) | \( g_2 \) | \( f, 10^4 \) |
|----|------------------|------------|------------|------|------|--------|
| 1  | 484.79           | 16.75      | 19.3       | 4    | 2    | 150    |
| 2  | 480.6            | 16.4       | 19.22      | 6    | 6    | 300    |
| 3  | 476.48           | 17.26      | 19.87      | 2    | 4    | 390    |
| 4  | 465.79           | 17.14      | 19.8       | 4    | 2    | 130    |
| 5  | 460.96           | 18.45      | 21.14      | 6    | 8    | 390    |
| 6  | 454.5            | 17.14      | 19.87      | 4    | 4    | 130    |
| 7  | 448.18           | 18.73      | 21.5       | 6    | 6    | 150    |
| 8  | 433.53           | 11.83      | 14.69      | 3    | 3    | 110    |

The presence of a total LTE in the spark channel plasma can be verified by Griem's criterion [6] for a homogeneous, nonstationary plasma: "if the electron densities are so large that the microscopic parameters of the plasma, such as the electron temperature and various densities, practically do not change over times on the order of the equilibrium time \( \tau_p = \frac{1.1 \cdot 10^7 z n_e^2 E_a^2}{f_2 n_e (n_e + n_e^{-1}) E_0} \left( \frac{kT_e}{z^2 E_0} \right)^{1/2} \exp \left( \frac{E_a}{kT_e} \right) \) and are also large enough to fulfill the criteria for the applicability of LTE in a homogeneous stationary plasma, but in these conditions in an unsteady plasma, indeed, an LTE state is achieved." Here \( n_e, n_a \) are the concentration of electrons and atoms, \( E_a^2 \) is the first excited level energy, \( E_0 \) is the ionization energy, and \( f_2 \) is the strength of the oscillators. Criterion for establishing of a local thermodynamic equilibrium in stationary plasma is \( n_e \geq 9 \cdot 10^{17} \left( \frac{E_a}{E_0} \right) \left( \frac{kT_e}{E_0} \right)^{1/2} \). As for the diffuse channel, it is hardly possible to speak of a full LTE. Therefore, the requirement of establishing a partial local thermodynamic equilibrium (PLTE) leads to the establishment time

\[
\tau_p \approx \frac{4.5 \cdot 10^7 z^3}{n^4 \cdot n_e} \left( \frac{kT_e}{z^2 E_0} \right)^{1/2} \exp \left( \frac{2zE_0}{n^4 kT_e} \right). \] (1)

Here \( n \) is the principal quantum number.

According to Eqn. (2), for lines of 480.6 nm and 484.7 nm, the PLTE is set at \( n_e \sim 10^{17} \text{ cm}^{-3} \) and \( kT_e = 3 \text{ eV} \) for a time less than \( \sim 10^{-9} \text{ s} \). Consequently, it is possible to determine the temperature of
the electrons for the plasma of the pre-spark diffuse channel. The value of the electron temperature, calculated from the relative intensity of the ArII spectral lines at the discharge current of 50 A, turned out to be equal within the error of the experiment, which indicates the reliability of the measurements. [4,7] The electron temperature, determined from the Eqn. (1) for the instant $t=40$ ns after the onset of a sharp current increase is equal to $T_e=5.2 \times 10^4$ K. The equalization time for the electron and ion temperatures can be determined from the rate of energy transfer from electrons to ions. The frequency of electron-ion collisions is $\nu = \frac{n_e e^4 \beta}{m} \frac{\ln \Lambda}{(kT_e)^2}$, and the time of energy transfer is $\tau_{ei} = (\delta \nu_{ei})^{-1} = \frac{M}{m} \frac{(kT_e)^2}{e^4 n_e \beta}$. Since the moment the gap is closed by a bright spark channel, the magnetic field leads to an increase in the temperature of the plasma of the channel. Table 2 gives the values of the temperature $T$ for various magnetic field strengths $H$ in the rapid expansion stage ($t = 300$ ns).

Table 2. The values of the electron temperature $T_e$ calculated by the method of relative intensity of the spectral lines, with a change in the value of the strength of the external magnetic field $H$.

| $\lambda$, nm | $T \times 10^4$, K |
|--------------|------------------|
|              | $H=0$ | $H=140$ kOe | $H=200$ kOe |
| 448.18       | 3.6   | 3.9          | 4.3          |
| 454.5        |       |              |              |
| 480.6        | 3.9   | 4.4          | 4.8          |
| 476.4        |       |              |              |
| 484.7        | 3.6   | 3.8          | 4.26         |
| 476.49       |       |              |              |
| average      | 3.7   | 4.03         | 4.41         |

The time-dependence of the temperature determined by the relative intensities of the spectral lines method is presented in the Fig. 3a.

Figure 3 (color on-line): (a) the time-dependence of the spark plasma temperature; (b) the dependence of the relative intensity of the spark channel radiation on the wavelength: 1) $H = 0$; 2) $H = 140$ kOe; 3) $H = 200$ kOe.
As we can see, the plasma temperature increases in an external longitudinal magnetic field. The electron density in the channel plasma is estimated from the Stark broadening of the spectral lines of argon ions ($n_e \sim 10^{18}$ cm$^{-3}$). The electron density in the plasma of the initial stages of the discharge is determined from broadening of the atomic argon lines. The value of the concentration of charged particles $\sim 10^{17}$ cm$^{-3}$ is close to the equilibrium value at $T_e \approx 10^4$ K.

In a magnetic field, the intensity of continuous radiation and the intensity of the spectral lines in the UV region increase. The brightness of the spectral lines in the visible region decreases slightly. As the intensity of the magnetic field increases, the maximum intensity of the continuous radiation shifts to the short-wavelength region (Fig. 3b). This result can be used to form pulses of radiation with a controlled spectral composition in the ultraviolet part of the emission spectrum.

Investigations of the effect of an external longitudinal magnetic field on the density and temperature of the plasma have shown that it reduces to a decrease in the inhomogeneity in the distribution of the gas dynamic functions. Moreover, the presence of an external magnetic field $H$ reduces the rate of expansion of the spark channel plasma with a simultaneous increase in the concentration $n_e$ and temperature of $T_e$ electrons. In this case, the main mechanisms of energy dissipation are bremsstrahlung and recombination radiation. Radiation thermal conductivity under the experimental conditions can be neglected [4].

4. Conclusion
As the magnetizing force increases, the maximum value of the continuous radiation moves to the region of short wavelengths; the intensity of the radiation increases.

The concentration of charged particles in the spark channel at the initial stages of its development is $\sim 10^{18}$ cm$^{-3}$. The electron density at the stage of the plasma streamer of the spark discharge is close to the equilibrium one and is $\sim 10^{17}$ cm$^{-3}$.

The increase in the temperature and density of the channel plasma is caused by the action of an external longitudinal magnetic field. By increasing the rate of energy input, it is possible to increase the specific power, conductivity, and plasma temperature of the values necessary for the obtaining of high-temperature plasma in small volumes. The detection of new spectral lines, from the experimentally obtained numerous spectrograms of radiation, in the case of a breakdown of Ar in an external critical longitudinal magnetic field gives a chance to assume the presence of the new elements formation.

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