Energy characteristics of high-pressure gas breakdown in strong longitudinal magnetic fields

O A Omarov¹, N O Omarova¹, P Kh Omarova¹ and A A Rukhadze²

¹ Dagestan State University, ul. Dzerzhinskogo 12a, Makhachkala, 367000 Russia
² Prokhorov General Physics Institute of the Russian Academy of Sciences, ul. Vavilova 38, Moscow, 119991 Russia

E-mail: inporao@mail.ru

Abstract. Investigations of the magnetic field influence on energy (power) released in discharge, the electronic temperature, particle concentration, and the radiation of plasma of the channel-arc stages has a practical focus. It was found that the magnetic field leads to an increase in current density, conductivity, and specific energy input and a decrease in the formation times of all stages of discharge development, transverse integral radiation, and channel expansion rate, and shifts in the maximum spectral density of radiation in the ultraviolet region with simultaneous generation of new spectral lines. The magnetic field decreases the rate of spark channel expansion and the loss of transverse radiation and increases the specific power, conductivity and temperature of the plasma at channel-arc stages, creating conditions for obtaining a hot plasma.

1. Introduction
In experiments, the avalanche-streamer stage \( n_e \sim 10^{18} - 10^{19} \text{ m}^{-3} \) has been successively developed, leading to the formation of a volumetric glow discharge \( n_e \sim 10^{20} - 10^{22} \text{ m}^{-3} \). As a plasma streamer reaches the cathode surface, the electric field intensifies \( \geq 10^8 \text{ V/m} \), which forms a cathode spot on the electron beam source \( (j = 10^9 \text{ A/m}^2, n \approx 10^{16} \text{ m}^{-3}, v \geq 10^7 \text{ m/s}) \) that drifts through the plasma of a glow discharge with the formation of a plasma channel with a diameter of \( d \sim 10^{-4} \text{ m} \) with simultaneous enhancement of the electron emission and current. The energy channel is poured into the spark channel, which leads to its sharp expansion at a velocity of \( \geq 10^3 \text{ m/s} \). Taking into account that the spreading velocity of the spark channel is greater than the diffusion rate of the magnetic field lines into the channel plasma, the expanding plasma front of the spark channel shifts the magnetic field lines, reducing them in the center and amplifying them at the electrodes (cathode and anode). This leads to the formation of a magnetic mirror and limitation energy losses with a simultaneous increase in thermal energy of the plasma [1–3].

Plasma channel parameters were determined to be dependent on the external magnetic field, and its radial development with the formation of shock waves, conductivity, radiation, and temperature and changes in the energy balance were analyzed in this study.

2. Formation and development of the high-pressure discharge plasma channel
An experimental study of the radial temperature distribution in the channel of a high-current discharge confirmed the non-uniformity of the distribution, which suggested that the radial distribution of the gas dynamic parameters in the spark channel is mainly determined by the discharge parameters.
Investigations of the influence of the magnetic field on the density and temperature of the plasma have shown that the influence of the field reduces to a decrease in the inhomogeneity in the distribution of the gas-dynamical functions.

A constant temperature in the spark channel was observed with very wide limits for the change in the rate of energy input, which allowed us to assume that the saturation of the emission brightness of the spark channel is related to the presence of a limiting value of the temperature of the spark channel plasma.

At energy inputs (E/p ~ 10–15 V/cm·Torr), a single plasma channel with a diameter of d ~ 10^{-4} m formed. The energy input into the channel increases the plasma pressure for some period (~10^{-9} s), which leads to expansion of the plasma channel in the radial direction with supersonic speed (~10^{3} m/s). The expanding plasma piston presses on the neutral gas, forming a shock wave of high intensity that is capable of transferring the ionization front in the radial direction.

The expansion of the plasma region across the magnetic field, whose pressure is p_H = \mu_0H^2/2, is commensurate with the gas kinetic pressure (p_R = nkT_e) of the plasma in the presence of a field gradient at the channel boundary at a lower rate. The gradient magnitude is determined by the rate of expansion and the conductivity of the plasma. Because the expansion velocity of the channel plasma decreases significantly in the external magnetic field from an equal gas kinetic pressure and magnetic value of p_H = p_R, it is possible to estimate the initial temperature of the spark channel plasma at H = 8·10^6 A/m with p = 2280 Torr, U_{sat} = 5 kV, and d = 0.003 m. It follows from the equality that to slow the channel expansion velocity, the plasma temperature should be \geq 10^7 K.

\[ T_e = \frac{\mu_0 H^2}{2nk} = 4.8 \cdot 10^6, K \]

where \( \mu = 1, \mu_0 \) is the magnetic constant (4\( \pi \) \cdot 10^{-7} H/m), k is the Boltzmann constant, \( n = 10^{24} \text{ m}^{-3} \), H = 8·10^6 A/m, and T_e is the electron temperature.

The rate of radial expansion for the high-pressure pulsed discharge channel observed in experiments cannot be provided either by diffusion or photoionization mechanisms [4, 5] and is possibly related to electronic thermal conductivity.

As shown from the GFR of the discharge channel an Ar atmosphere, the boundary of the discharge channel and the front of the shock wave coincide up to a certain point in time, and only after 400–500 ns does the shock wave separate from the channel boundary. The velocity of channel expansion for 100 ns equals 1.5·10^7 m/s for H = 0 and 0.9·10^7 m/s for H = 7.2·10^6 A/m.

The combination of the electrical characteristics of the discharge (current, voltage) as a function of time, and the pattern of its space-time development makes it possible to calculate the conductivity, current density, specific energy input, etc.

Comparisons of the current and voltage oscillograms for the plasma channel radius make it possible to determine the power released in the discharge at various stages of its formation and development [6, 7].

In a single fully ionized plasma channel, the temperature was determined by the Spitzer formula. The magnetic field increases the density of the current saturation by several times. As the resistance decreases, the discharge goes into an oscillatory mode. The transition moment is determined by the condition of equality of the impedance of the circuit and the active resistance of the channel:

\[ R(t) \approx 2\rho_0 = 2 \left( \frac{L}{C_1} \right)^{1/2} \approx 0.46, (\Omega) \]

where L is the discharge circuit inductance and C_1 is the storage capacitance. The characteristic impedance is at L = 5·10^{-5} H, and C_1 = 1·10^{-4} F is 0.46 \( \Omega \).

The increase in current leads to an increase in the rate of energy input into the discharge. According to the phase-shifted current and voltage oscillograms, the power and energy introduced into the plasma channel of the spark were determined. With the formation of a spark channel, the power during the first 60–80 ns sharply increases to the maximum value (\geq 10^{15} W/m^3).
In the longitudinal magnetic field, the specific power \[4\] that was introduced into the discharge increased. We estimated the plasma channel temperature of the spark channel, assuming that 0.1 part of the energy was deposited in the discharge per 100 ns, which was used to increase the thermal energy of the plasma \(p_E = jE \approx 10^{15} \text{ W/m}^3\), \(\Delta t = 100 \text{ ns}, n = 10^{24} \text{ m}^{-3}, W_E = p_E \Delta t = W_T = nkT, T = p_E \Delta t/nk \approx 10^7 \text{ K}\).

The current density in the emerging spark channel was 30–40 ns after the onset of a sharp decrease in voltage across the gap (from the moment of formation of the cathode spot, which reaches a value of \(\approx 10^{10} \text{ A/m}^2\)).

The conductivity of the channel plasma during the first 100 ns increases, and in the future, practically does not change.

In a longitudinal magnetic field, the conductivity increases with increasing field. The rapid increase in the conductivity of the spark channel plasma for the first 100 ns indicates an increase in the degree of ionization. Because, in the future, conductivity remains practically unchanged, it can be assumed that at the instant of establishing the maximum conductivity, the degree of plasma ionization is nearly 100%.

In highly ionized plasma, for the quasistationary channel–arc stage of a high-pressure pulsed discharge, the conductivity of the plasma depends on \(T_e\), and the energy losses are determined by the radiation. When \(v_{ea} < v_{ei}\), the specific electrical conductivity of the plasma is determined by the Spitzer formula \[5–7\],

\[
T_e^2 \approx 10^3 \sigma, K
\]  \hspace{1cm} (1)

where \(T_e\) is the temperature in K and \(\sigma\) is the specific electrical conductivity \((\Omega^{-1}\text{m}^{-1})\). The values calculated from formula (1) for Ar and air show that with increasing magnetic field strength up to 24·10^5 A/m the conductivity and temperature of the plasma of the channel-arc stage of the spark increase.

As the experimental results have shown, an external longitudinal strong magnetic field that accelerates the formation of all the stages of a discharge with a simultaneous increase in the specific energy input, temperature, and electron concentration leads to the formation of new spectral lines in the short-wave part of the spectrum. With increasing external magnetic field strength up to 3.2·10^7 A/m, new spectral lines appear at \(\lambda_3 = 279.67 \text{ nm (Rh}, \text{ rhodium, or osmium)}, \lambda_4 = 307.03 \text{ nm (Mn}, \text{ manganese)}, \lambda_5 = 330.25 \text{ nm (Zn}, \text{ zinc)}, \lambda_6 = 332.37 \text{ nm (Ar}, \text{ argon)}, \lambda_7 = 335.64 \text{ nm (Ar)}, \lambda_8 = 340.15 \text{ nm (Ar)}, \lambda_9 = 340.14 \text{ nm (Ar)}, \lambda_{10} = 336.45 \text{ nm (Ar)}. \text{ Meanwhile, some lines at H = 0 with wavelengths of } \lambda_1 = 310.43 \text{ nm and } \lambda_2 = 314.48 \text{ nm in the magnetic field of 3.2·10^7 A/m disappeared.}

The maximum radiated energy in a magnetic field shifted to the short-wave region of the spectrum, which is a consequence of the increase in the plasma temperature.

3. Conclusions

From analysis of the experimental data, we conclude that it is possible to obtain a hot plasma in the course of breakdown of high-pressure gases in short intervals in strong longitudinal magnetic fields to create a source of intense ultraviolet or X-ray radiation for the creation of a pulse-periodic thermonuclear reactor.

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