Possibility of obtaining hot plasma during the breakdown of high-pressure gases in strong magnetic fields

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Abstract. The hot plasma production during the high-pressure gas breakdown in the strong magnetic fields with a magnetic strength \( H \) of up to \( 16 \times 10^6 \) A/m was considered experimentally. The breakdown occurred in a short gap as a result of interaction of the monoenergetic electron beam \( (n_e \sim 10^{18} \text{ m}^{-3}, \text{ energy is about several keVs}) \) with dense plasma \( (n \sim 6 \times 10^{22} \text{ m}^{-3}) \). The breakdown leads to the formation of the magnetic trap (magnetic mirror), and the discharge plasma becomes heated due to the electron beam, electron cyclotron resonance, and Joule heating processes. The studies have shown that the use of the strong longitudinal magnetic fields results in an increase in the specific power, conductivity, and plasma temperature.

Introduction

In the presence of the strong magnetic fields, creating anisotropy both in gas and plasma, the gas breakdown in all its stages demonstrates some new important features. In order to obtain an intense radiation source in the ultraviolet region, the plasma conductivity and temperature can be increased by means of increasing the specific energy and the rate of its input into the spark channel plasma placed inside the strong longitudinal magnetic field. In this connection, the studies of the effect of the external longitudinal magnetic field on such high-pressure discharge parameters as the energy and power released in the discharge, the electron temperature, and the particle density are of particular interest. The breakdown current-voltage characteristics were measured at different external longitudinal magnetic fields, and the energy deposition into the discharge gap was determined from them.

Due to the fact that the expansion rate of the spark channel is higher than the diffusion rate of the magnetic field lines inside the channel plasma, the expanding front of the spark channel plasma causes the displacement of the magnetic field lines, decreasing the magnetic field in the center and increasing it near the electrodes (cathode and anode). In the formed magnetic configuration, the energy losses are reduced and the internal plasma energy increases. Thus, in the strong longitudinal magnetic field, the plasma channel (formed as a result of the electron beam drift) becomes a magnetic trap [1–3]. In the present work, the issues concerning the hot plasma formation during the breakdown of high-pressure gases in the longitudinal magnetic field are considered.

Thus, the goal of this work is to develop a technique that provides achieving optimal parameters for the hot plasma production. On the one hand, the solution of this problem will contribute to deeper understanding the mechanisms of physical processes involved, and on the other hand, it is of particular interest due to the provided information on the little-studied objects in the theory of dynamic systems.

In this article, we systematize some results of our recent studies.
Experiment
The experimental setup consisted of two independent electrical circuits operating synchronously: the pulsed voltage generator and the pulsed magnetic field generator. Synchronous operation was provided by the synchronization unit. The discharge gap was exposed to ultraviolet (UV) radiation of the spark discharge located at a distance of 5–7 cm from its axis. In this arrangement, the spark discharge forms the initial electron density, which is the same along the axis and across section. To ionize the initial gas by UV-radiation, the system based on the TGI1-400/16 thyratron was used. UV radiation from the discharge with energy content of 0.3–0.4 J increases the seed electron density \( n_0 \) up to \( 10^{12}–10^{14} \) m\(^{-3}\). The external magnetic field was created by means of discharging the capacitor bank through the solenoid, inside which the gap under study was installed [4]. When designing the solenoid, we took into account the required magnetic field, as well as the requirements of mechanical strength and simplicity of the construction. The discharge radiation was recorded through the side apertures provided in the central 1-cm-thick solenoid coil. The solenoid was an all-metal structure made of beryllium bronze with 33 coils, an inner diameter of 0.8 cm, and an inductance of \( L_0 = 5 \times 10^{-8} \) H.

The voltage at the discharge gap was recorded using the OK-21 and C8-14 oscilloscopes, which detect the signal from the capacitive divider. To record the discharge current in different discharge stages, different techniques were used. Low currents were measured using oscilloscope, which recorded the signal from a low-inductance shunt of 1–2 \( \Omega \) connected in series with the discharge gap. In the high current discharge stages, the Rogowski belt was used. The signal from the Rogowski belt was applied to the plates of the OK-21 oscilloscope. The resistance of the discharge plasma was determined using the equation 
\[
R(t) = (U(t) - L_e \frac{dI}{dt}) / I(t),
\]
where \( L_e \) is the discharge circuit inductance (5 \( \times 10^{-8} \) H), and \( U \) is the voltage drop across the discharge gap. Using the known discharge cross section and current, the discharge current density and electron density were determined.

The space-time development of the discharge was studied using the FER2-1 image-converter camera. The accuracy of synchronization of the discharge glow images with the current or voltage was approximately 2–3 ns. The synchronization was performed by applying the current (or voltage) pulse to the deflecting plates of the electron image tube (UMI-92), which triggered the discharge glow scanning. In this case, the time delay between the light and electric signals was taken into account. The joint analysis of the measured electrical characteristics and the space-time discharge photographs makes it possible not only to determine the current density and specific energy input, but also to trace the formation and the space-time evolution of the spark channel. The RF-3 film was used to take photographs of the discharge. To find the most strongly glowing region of the gap, the discharge glow photographs were taken with different relative apertures of the lens. The aperture ratio of the lens was maximally reduced when it was necessary to obtain image of the most brightly glowing region of the cathode plasma. The microphotometry of the spatial images was performed and the computer processing was involved. The size of the near-cathode plasma (diffuse channels connected to the cathode spots) determined in such a way turned out to be \( 2r = 0.01–0.02 \) cm.

In order to clarify how the power released during the breakdown of gaseous argon depends on the magnitude of the magnetic field, the energy input into the plasma was determined at a pressure \( p = 2280 \) Torr. The distance between the electrodes was \( d = 0.3 \) cm, and the voltage applied to the discharge gap was approximately \( U_{br} = 7 \) kV, an overvoltage being of 55% [4].

Results and discussion
The studies have shown that, with increasing pressure, overvoltage, and the magnetic field, the specific energy input into the spark channel plasma increases over times of the order of \( \sim 10 \) ns that results in an increase in the electron density \( n_e \) and temperature \( T_e \). The transient period for establishing the thermodynamic equilibrium between the electron and ion components in the spark channel is several nanoseconds [3–5].

In the expanding spark channel, the current density becomes saturated. Despite the rapid expansion of the channel, the current density remains constant. In the presence of the magnetic field, the current
density is higher in all discharge stages. So, for example, at a magnetic field of \( H = 16 \cdot 10^6 \) A/m, in 100 ns after the sharp drop in voltage occurs, the current density was \( 3.6 \cdot 10^5 \) A/cm², while, at \( H = 0 \), the current density was only \( 2.2 \cdot 10^5 \) A/cm².

A fast increase in the spark channel plasma conductivity occurring during the first 100 ns indicates an increase in the degree of ionization. In the channel-arc discharge stage, the electron temperature is determined by the plasma conductivity, in accordance with the following ratio:

\[
T_e \approx 1.4 \cdot 10^3 \cdot \sigma^{2/3} [\text{K}].
\]  

(1)

The time of energy transport from electrons to ions is \( \tau_{ei} \sim (\delta \cdot v_{ei})^{-1} \), where \( v_{ei} = n_e \frac{e^2 \ln \Lambda}{(kT_e)^2} \) is the frequency of electron-ion elastic collisions, \( n_e \) is the electron density, \( \ln \Lambda \) is the Coulomb logarithm, \( e \) is the electron charge, \( k \) is the Boltzmann constant, \( T_e \) is the electron temperature, \( v \) is the average speed, and \( \delta \approx \frac{2m}{M_i} \) (where \( M_i \) is the ion mass). At a charged particle density of \( \sim 10^{24} \) m\(^{-3}\) and an electron temperature of \( T_e \approx 30 \) eV, the frequency of electron-ion collisions is \( v_{ei} \approx 10^{10} \) s\(^{-1}\), and the time of energy transport is \( \tau_{ei} \sim \left( \frac{2m}{M_i} v_{ei} \right)^{-1} \approx 10^{-8} \) s.

Thus, the above estimates show that, in the spark channel plasma (\( n_e \sim 10^{24} \) m\(^{-3}\)), over times of approximately \( 10^{-8} \) s, the electron and ion temperatures become equal, i.e. \( T_e = T_i \) [6]. The plasma can be characterized by the single temperature determined by equation (1).

The external sources of electric energy that create ionized plasma in the channel-arc stage of the high-pressure discharge transfer it to the electron plasma component, since electrons are the current carriers. Ions acquire thermal energy in collisions with electrons. The fraction of the kinetic energy that can be transferred from electron to ion in collision does not exceed \( 4m/M_i \), where \( m_e \) and \( M_i \) are the electron and ion masses. Since \( M_i \gg m_e \), electron must collide several thousand times to completely transfer its energy to ions.

Table 1 presents the experimental data on the voltage \( U(t) \), current \( I(t) \), radius of the spark channel \( r(t) \), as well as the resistance \( R(t) \), specific conductivity \( \sigma(t) \), and electron temperature \( T_e \) calculated at \( H = 1.6 \cdot 10^5 \) A/m, \( d = 0.3 \) cm, \( p = 2280 \) Torr, and \( U_{br}(t) = 6.65 \) kV.

| # | \( t \), ns | \( r \) \( \times 10^3 \), m | \( I \), kA | \( U \), kV | \( P \), \( 10^{-3} \) W | \( \sigma \), \( 10^{-1} \), \( \Omega^{-1} \) m \(^{-1}\) | \( T_e \), \( 10^{2} \), K | \( J \), \( 10^{-3} \), A/m | \( E_{sp} \), \( 10^{8} \), J/m | \( E_{chan} \), \( 10^{7} \), J |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 149.6 | 6.099 | 6.269 | 38 |
| 2 | 153.3 | 6.992 | 6.045 | 42 |
| 3 | 156.5 | 7.55 | 5.781 | 44 |
| 4 | 164 | 9.037 | 5.566 | 50 |
| 5 | 173.8 | 0.1 | 10.93 | 5.078 | 55 | 2.08 | 3.5 | 34.79 | 5.25 | 15.75 |
| 6 | 174.7 | 0.11 | 10.97 | 4.775 | 52 | 2.22 | 3.67 | 31.08 | 4.90 | 16.52 |
| 7 | 177.6 | 0.11 | 11.83 | 4.228 | 50 | 2.3 | 3.73 | 31.12 | 4.62 | 16.79 |
| 8 | 179.6 | 0.12 | 12.05 | 3.901 | 43 | 1.3 | 2.56 | 17.05 | 1.71 | 11.52 |
| 9 | 184.2 | 0.13 | 12.94 | 3.291 | 42.5 | 1.2 | 2.4 | 12.71 | 1.11 | 10.80 |
| 10 | 190.3 | 0.14 | 14.24 | 2.851 | 40 | 1.2 | 2.4 | 11.33 | 0.90 | 10.80 |
| 11 | 213.1 | 0.15 | 17.7 | 1.933 | 34.2 | 2.1 | 3.5 | 12.78 | 1.19 | 15.75 |
| 12 | 223.5 | 0.16 | 19.12 | 1.689 | 32.3 | 2.5 | 3.97 | 12.57 | 1.23 | 17.87 |
| 13 | 255 | 0.165 | 22.76 | 1.396 | 32 | 3.03 | 4.5 | 13.70 | 1.27 | 20.25 |
| 14 | 260 | 0.17 | 23 | 1.330 | 38.18 | 2.1 | 3.5 | 11.71 | 0.84 | 15.75 |
Conclusions

Summing up the presented work, we can draw the following conclusions:

(i) The characteristic time required for establishing equal electron and ion temperatures and equilibrium ionization in the high-pressure discharge plasma in the channel-arc discharge stage is $<10^{-8}$ s.

(ii) The presence of the longitudinal magnetic field provides an increase in the current density. At a magnetic field of $H = 1.6 \cdot 10^7$ A/m, in 100 ns after the sharp drop in voltage occurs, the current density was $3.6 \cdot 10^5$ A/cm$^2$, while, at $H = 0$, in the absence of the magnetic field, the current density was only $2.2 \cdot 10^5$ A/cm$^2$.

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