Formation and time development of spark channel in strong magnetic field

O A Omarov¹², N O Omarova¹ and P Kh Omarova¹

¹ Dagestan State University, Makhachkala, Russia
² E-mail: inporao@mail.ru

Abstract. The characteristics of the spark channel plasma formed in the external longitudinal magnetic field are studied experimentally. In experiment, the current-voltage, optical, and spectral characteristics of the discharge were measured and analyzed. Synchronization of the pulsed electric and magnetic fields was performed. The effect of the magnetic field on the radial expansion of the spark channel, the shock wave formation, as well as the changes in the balance of energy and temperature in the ionized plasma of the high-pressure gas discharge were analyzed. It was found out that, in the strong longitudinal magnetic field, the temperatures of electrons and ions in the spark channel ($n_e \approx 10^{18}$ cm$^{-3}$) become equal. The current density, the plasma channel conductivity of the spark channel, and the specific energy deposition into the discharge increased. The channel plasma parameters were analyzed as functions of the external magnetic field.

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. 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.

Despite the fact that the studies on obtaining the controlled fusion reaction in gas-discharge plasma have been performed since the fifties of the twentieth century [1–3], no significant results were obtained in this field of research. This is primarily due to the fact that the low-pressure discharges and the insufficiently strong magnetic fields were used. At the same time, the recent studies have shown that this it is quite possible to detect fusion reactions in a small volume with the magnetic fields of the order of several hundred kOe.

This work is aimed to experimentally and theoretically study the process of the spark channel formation in the high-pressure discharges in argon in the external magnetic field.

Experiment

The experimental arrangement and techniques used are described in detail in [4–6]. The discharge was initiated in the gap formed by the two Rogowski-type aluminum electrodes with diameters of 0.8 cm installed at a distance of $d = 0.3$ cm from each other. The pressure was $p = 2280$ Torr and the breakdown voltage was $U_{br} = 7$ kV. The UV radiation source was used for the initial preionization, which increases the seed electron density up to $n_0 \approx 10^8-10^9$ cm$^{-3}$. Voltage pulses with adjustable amplitude of up to 30 kV and a rise time of $\approx 10$ ns were applied to the electrodes. The voltage applied
to 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 Ω 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 column was determined using the equation $R_p(t) \approx (U(t) - L \frac{dI}{dt})/I(t)$, where $L_c$ is the discharge circuit inductance ($5 \cdot 10^{-8}$ H), and $U(t)$ 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 electron temperature of highly ionized plasma can be determined using the well-known Spitzer formula

$$\sigma = 3.06 \cdot 10^{-3} \cdot T_e^{3/2} \cdot (z \cdot \ln \Lambda)^{-1} \text{ (Ω cm)$^{-1}$}$$  \tag{1}

Here $T_e$ is the electron temperature in K units, $z$ is the ion charge, $\ln \Lambda$ is the Coulomb logarithm, which is usually assumed to be 10–15. The plasma conductivity was determined using data on the spark channel resistance.

The power and energy deposited into the discharge were determined using data on the known resistance and current, $P(t) = R_p(t)I^2(t)$, $E(t) = \int_0^t P(t) \cdot dt$.

The space-time development of the discharge was studied using the FER2-1 streak 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 images makes it possible not only to determine the current density and specific energy deposition, but also to trace the formation and the space-time evolution of the spark channel. The microphotometry of the spatial images was performed and the computer processing was involved.

**Experimental results**

At low overvoltages, the narrow single spark channel with a diameter of 0.01 cm is formed, which has a considerable spreading rate of $\sim 10^9$ cm/s. Due to the fast energy deposition into the thin channel, the plasma pressure sharply increases in very short time (~1 ns), which makes the spark channel plasma to expand in the radial direction at a supersonic speed ($\sim 10^5$ cm/s). The expanding plasma “piston” exerts pressure on the neutral gas, thereby forming a high intensity shock wave transferring the ionization front in the radial direction.

In the presence of the field gradient at the spark channel boundary, the plasma expansion across the magnetic field, the pressure of which is comparable to the plasma gas kinetic pressure, occurs at lower speed. The field gradient is determined by the expansion rate and plasma conductivity [4–7]. In the absence of the magnetic field ($H = 0$), at the 100 ns, the expansion rate was $1.5 \cdot 10^5$ cm/s, and at a magnetic field of $H = 90$ kOe, it was $0.9 \cdot 10^5$ cm/s. Typical streak camera frame images of the spark channel can be found in [4, 5].

The time dependences of the channel radius at different magnetic fields are presented in [6, 7] that clearly show that, up to a certain time, the boundary of the discharge channel coincides with the shock wave front.

The current density in the forming spark channel can be calculated in accordance with the formula

$$j(t) = \frac{I(t)}{\pi r^2(t)}.$$
Despite the rapid expansion of the channel, the current density remains almost unchanged, that is, it becomes saturated. This indicates that the plasma conductivity is reduced [8]. However, an external magnetic field of \( H = 180 \text{ kOe} \) increases the saturation level of the current density by several times. In 30–40 ns after the beginning of a sharp decrease in the voltage across the gap (after time of the cathode spot formation), the current density amounts to \( \sim 10^9 \text{ A/cm}^2 \).

Let us calculate the power released in the discharge plasma.

The total energy that is released during the discharge in the discharge gap and the corresponding circuit is equal to energy stored in the capacitor \( (U_{br} = 7 \text{ kV}, L = 5 \cdot 10^{-8} \text{ H}, \text{ and } C = 1 \text{ \mu F}); W_0 = \frac{CU_{br}^2}{2} = 24.5 \text{ J}. \)

During the discharge, energy is distributed between the energy stored in the capacitor \( W_C(t) = \frac{CU^2(t)}{2} \), the magnetic field energy of the current \( W_I(t) = \frac{LI^2(t)}{2} \) and the energy released on the active resistance \( Q(t) \). The sum these energies is equal to \( W_0 \), whence it follows that \( Q(t) = \frac{CU^2(t)}{2} - \left( \frac{CU^2(t)}{2} + \frac{LI^2(t)}{2} \right) \). The energy \( Q \) includes both the energy spent on the heating of the circuit elements and the energy released in the channel. The last one, in turn, consists of the components spent on the excitation and ionization of atoms, the channel expansion, radiation and thermal heating, which together form the "effective" active resistance of the channel. If \( R < R_c = \frac{L}{\sqrt{C}} \), the oscillatory mode can be settled.

Only a part of the total energy is released in the discharge gap, which is determined by the ratio of the active gap resistance to the total active circuit resistance. The instantaneous released power is equal to the time derivative of the \( Q \) energy: \( W(t) = \frac{dQ(t)}{dt} \).

**Figure 1.** Dependence of the maximum instantaneous released power \( W_{max}(t) \) on the ratio \( R/R_c \) of the gap resistance to the total resistance of the circuit.

Figure 1 shows the dependence of the maximum instantaneous released power \( W_{max}(t) \) on the ratio \( R/R_c \) of the gap resistance to the total resistance of the circuit. As can be seen, with decreasing resistance \( R \), the maximum power released in the discharge (in MW) first increases, and then decreases. The maximum is reached at \( R = 0.56R_c \), Moreover, in the range from approximately \( 0.3R_c \) to \( R_c \), the maximum released power is within 90% of its maximum value, and the bulk of the initial energy is released during 350–400 ns, which, in this case, is of the order of 60 MW. In the longitudinal magnetic field, the specific power [9] deposited into the discharge also increases. In the forming spark channel, a large energy fraction is spent on the gas ionization and the channel expansion, while, in the subsequent stages, almost all the deposited energy is spent on radiation.

Thus, temperature estimates [1, 4] show that, in the spark channel \( (n_e \sim 10^{18} \text{ cm}^{-3}) \), the electron and ion temperatures become equal, i.e. in the plasma of the forming spark channel, neutral atoms
“burn out” over several tens of nanoseconds, and the temperatures of electrons and ions become equal, \( T_e \approx T_i \). The plasma can be characterized by the single temperature determined by equation (1). Solving the Saha equation for the higher degrees of ionization, we obtain that the density of doubly ionized Ar atoms is equal to approximately 30% of the density of singly ionized Ar atoms, and the concentration of Ar\(^{3+}\) ions is also considerable [9–11].

**Conclusions**

(i) In the spark channel plasma, the characteristic time required for setting equal temperatures of electrons and ions, as well as the equilibrium ionization, is \( \sim 10^{-8} \) s. The degree of the channel plasma ionization is almost one hundred percent and the concentrations of singly, doubly and, triply ionized Ar atoms are considerable.

(ii) The presence of the longitudinal magnetic field \( H = 200 \) kOe results in an increase in the current density, plasma conductivity, specific energy deposition into the discharge, and plasma temperature.

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