The construction of a pulsed-periodic thermonuclear reactor using high pressure gases in strong magnetic fields

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Abstract. Experiments on a spark discharge (E/p ~ 1000 V/m·Torr) showed that the formation of a hot plasma in a strong magnetic field (H < 3.2·10⁷ A/m, λ > rₗₐₛ) produced the breakdown of high-pressure gases in short intervals. This was due to mono-energetic electron beam formation (nₑ ~ 10¹⁸ m⁻³ and duration ~10⁻¹¹ s) and its interaction with the dense plasma (n ~ 6·10²² m⁻³). This lead to beam, cyclotron resonance and ohmic heating of the electrons in the plasma.

1. Introduction
The magnetic field increases the specific power, conductivity, and plasma temperature (at channel-arc stages), creating conditions for obtaining a hot plasma that is heated by an electron beam. This leads to a shift in the maximum spectral density of the channel plasma emission into the ultraviolet and X-ray regions and the formation of new spectral lines [1–3].

2. Experimental methods
A complete description of the experimental installations and methods of investigation is provided in refs. [2, 3].

3. Results and discussion
First, a magnetic field was created in the gap (with a period of ≈600 μs); then, the gap as irradiated with ultraviolet (creating pre-ionization with an electron concentration of nₑ ~ 10¹²–10¹⁴ m⁻³) followed by a pulsed electric field, which leads to the development from the anode in the whole gap volume of the plasma streamer, forming a glowing volume discharge with an electron density of ~10²⁰–10²² m⁻³ [4, 5]. When the plasma streamer reached the cathode surface, the electric field was amplified during the formation of the cathode spot. The source of the thermonionic beam with an energy of 10 keV (j = 10⁷ A/m², n ~ 10¹⁸ m⁻³, v = 10⁷ m/s and duration ~10⁻¹¹ s) drifted through the plasma of the glow discharge, forming a strongly ionized plasma channel with a diameter of 2r ~ 0.0001 m [4, 5]. In the plasma channel, an electron beam with several keV of energy was introduced at time ≤10⁻¹¹ ns, leading to a sharp increase in the plasma channel temperature and its explosive expansion with a shock wave.

A completely expanding ionized plasma of the channel shifted the lines of force of the magnetic field, reducing their density in the center and amplifying them at the electrodes (cathode and anode). This system can be represented as a magnetic adiabatic trap, which limits energy losses with a simultaneous increase in the plasma temperature [6].
Thus, in Ar, \( p = 2280 \) Torr and \( E/p \approx 1000 \) V/m·Torr in a magnetic field in a completely ionized plasma channel with a density of \( n_e \approx 10^{26} \) m\(^{-3}\) and a discharge duration \( \tau \approx 10 \) µs; an adiabatic magnetic trap formed in which the plasma was heated up to 100 eV. This was confirmed by the amplification of the plasma radiation in UV and X-ray spectral regions and the appearance of new spectral lines [5]. Plasma-beam interaction was realized in the magnetic mirror, which lead to heating of the energetic electrons and a significant increase in the transverse dimensions of the plasma [8–11].

In ref. [3], a scheme for a pulsed electric fields generator is shown, where the capacitance is \( C_1 = 10^{-6} \) F, \( L_{\text{circuit}} \approx 6.6 \cdot 10^{-8} \) H, \( R_1 = 100 \) kΩ, and 2 is the switching arrester. For \( R \approx R_1 \) and \( 1/L_{\text{circuit}}C \ll R^2/4L^2 \), there is an aperiodic discharge, for \( R \to 0 \) \( 1/L_{\text{circuit}}C \gg R^2/4L^2 \), there are damped natural oscillations. \( R_{\text{can}} \) with free oscillations in the circuit should be significantly less than 0.46 Ω. Taking this value into account, we obtain

\[
\sigma = \frac{d}{R(t)\pi^2} \geq 1.9 \cdot 10^6 (\Omega \cdot m)^{-1},
\]

\( \sigma \approx 10^{-3} T^{3/2}, T \approx 1.5 \cdot 10^6 \) K.

The maximum current is obtained from the relation, \( CU^2/2 = LI^2/2 \). At \( U_0 = 7 \) kV [12, 13], \( I_{\text{max}} \approx 2.8 \cdot 10^4 \) A, and at \( U_0 = 6.65 \) kV, \( I_{\text{max}} \approx 8.3 \cdot 10^4 \) A.

The concentration of particles in the plasma is determined by the Sakh distribution [6], which, when applied to higher degrees of ionization, gives the density of doubly ionized atoms equal to approximately 30% of the density of singly ionized atoms and significant concentrations of Ar\(^{+3}\) and Ar\(^{+4}\) ions.

Thus, with the expansion of the channel, this suggests the propagation of a region of high ionization and a shock wave over a weakly ionized plasma.

The maximum energy input corresponds to the onset of a sharp drop in voltage (the formation of a plasma channel with a density of \( n_e \approx 10^{26} \) m\(^{-3}\) and a discharge duration \( \tau \approx 10 \) µs; an adiabatic magnetic trap formed in which the plasma was heated up to 100 eV. This was confirmed by the amplification of the plasma radiation in UV and X-ray spectral regions and the appearance of new spectral lines [5]. Plasma-beam interaction was realized in the magnetic mirror, which lead to heating of the energetic electrons and a significant increase in the transverse dimensions of the plasma [8–11].

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The maximum energy input corresponds to the onset of a sharp drop in voltage (the formation of a narrow channel and its expansion). The maximum power dissipated in the channel for different values of the external magnetic field and for the current strength and voltage corresponding to this instant are

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For the channel inductance, \( L \approx 10^{-9} \) H. The \( U(t) \), \( I(t) \) and \( r(t) \) were found experimentally, and \( R(t) \) and \( \sigma(t) \) were calculated from the formulas for Ar as \( H = 0 \) and \( H = 12.8 \cdot 10^6 \) A/m and are shown in Tables 1 and 3 (\( U_{\text{alt}} = 6.65 \) kV, \( U_a = 5 \) kV, \( p = 2280 \) Torr, \( W = 33\% \), \( d = 0.003 \) m), respectively. Tables 2 and 4 show the values for air at \( H = 0 \) and \( H = 20 \cdot 10^6 \) A/m, respectively (\( U_{\text{alt}} = 7 \) kV, \( d = 0.002 \) m, \( p = 760 \) Torr, \( W = 20\% \)). The temperature was calculated using the Spitzer formula [6]

\[
T = 10^3 \sigma, K.
\]

### Table 1.

| \( H = 0, \text{Ar} \) | \( t, \text{ns} \) | \( r(t) \cdot 10^{-3}, \text{m} \) | \( I(t), \text{A} \) | \( U(t), \text{V} \) | \( R(t), \Omega \) | \( \sigma(t), (\Omega^{-1} \text{m}^{-1}) \) | \( T_e, \text{K} \) |
|----------------------|----------------|----------------|-------------|----------------|----------------|------------------|---------|
| 300                  | 0.47           | 12000         | 996         | 0.08           | 54546          | 144624          |         |

### Table 2.

| \( H = 0, \text{Air} \) | \( t, \text{ns} \) | \( r(t) \cdot 10^{-3}, \text{m} \) | \( I(t), \text{A} \) | \( U(t), \text{V} \) | \( R(t), \Omega \) | \( \sigma(t), (\Omega^{-1} \text{m}^{-1}) \) | \( T_e, \text{K} \) |
|------------------------|----------------|----------------|-------------|----------------|----------------|------------------|---------|
| 200                    | 0.17           | 6000           | 1500        | 0.25           | 132158         | 259248          |         |

Tables 3 and 4 show the electrical characteristics for the channel-arc stages of the spark in argon at \( H = 12.8 \cdot 10^6 \) A/m and in air at \( H = 20 \cdot 10^6 \) A/m. As shown from the tables, the conductivity and temperature of the channel plasma, \( \sigma \), increase in a strong external magnetic field.

For high-pressure pulsed discharges, a highly ionized hot plasma (\( T_e \approx T \)) with a sufficiently high temperature formed.
Table 3.

| t, ns | r(t)·10^{-3}, m | I(t), A | U(t), V | R(t), Ω | σ(t), (Ω^{-1}m^{-1}) | T_e, K |
|------|-----------------|--------|--------|---------|------------------------|-------|
| 300  | 0.22            | 13200  | 897    | 0.07    | 300000                 | 448140|

Table 4.

| t, ns | r(t)·10^{-3}, m | I(t), A | U(t), V | R(t), Ω | σ(t), (Ω^{-1}m^{-1}) | T_e, K |
|------|-----------------|--------|--------|---------|------------------------|-------|
| 200  | 0.15            | 12800  | 650    | 0.05    | 857142                 | 902237|

Let us estimate the conductivity and electron temperature of the channel-arc stage of a high-current discharge in argon and in air from the equality of volume density of the magnetic field energy, the density of the channel's thermal energy. Because the expansion velocity of the channel plasma decreases significantly in an external magnetic field from the ratio \( W_n \leq W_t \), it is possible to estimate the plasma channel temperature of the spark at \( H = 3.2 \cdot 10^7 \) A/m in Ar with a \( p = 2280 \) Torr, \( U_{alt} = 5 \) kV, and \( d = 0.003 \) m,

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

where \( \mu = 1 \), \( \mu_0 \) is the magnetic constant \( (4\pi \cdot 10^{-7} \text{ H/m}) \), \( k \) is the Boltzmann constant, \( n = 10^{25} \text{ m}^{-3} \), \( H = 3.2 \cdot 10^7 \) A/m, and \( T_e \) is the electron temperature.

For the initial stages of the spark channel, when \( r = 10^{-4} \) m and \( I = 0^3 \) A, the channel area is \( S = \pi r^2 = 3.14 \cdot 10^{-8} \) m². Because \( j = I/\pi r^2 \approx 0.32 \cdot 10^{13} \text{ A/m²} \) and \( jE \approx 10^{15} \text{ W/m}^3 \), then \( E \approx 10^4 \text{ V/m} \) and the conductivity is \( \sigma = j/E \approx 10^7 \Omega^{-1} \text{ m}^{-1} \). However, the conductivity is \( \sigma \approx 10^{-3} r^{3/2} \Omega^{-1} \text{ m}^{-1} \), from which it follows that the temperature equals

\[
T = \frac{3}{4}(\sigma r^{10^3})^{2/3} = \frac{3}{10^{24}} \approx 10^8, K
\]

The current density in a magnetic field at all stages is larger.

This increase in the conductivity of the spark channel plasma during the first 100 ns indicates an increase in the degree of ionization, which suggests that by the time that there is a maximum conductivity, the degree of ionization of the plasma becomes 100%.

A magnetic field up to \( 32 \cdot 10^6 \text{ A/m} \) leads to the formation of new spectral lines in the short-wave part of the spectrum: \( \lambda_3 = 279.67 \text{ nm} \) (Rh, rhodium, or osmium), \( \lambda_6 = 307.03 \text{ nm} \) (Mn, manganese), \( \lambda_5 = 330.25 \text{ nm} \) (Zn, zinc), \( \lambda_7 = 332.37 \text{ nm} \) (Ar, argon), \( \lambda_8 = 335.64 \text{ nm} \) (Ar), \( \lambda_9 = 340.15 \text{ nm} \) (Ar), and \( \lambda_8 = 366.45 \text{ nm} \) (Ar). Meanwhile, some lines at \( H = 0 \) with wavelengths of \( \lambda_1 = 310.43 \text{ nm} \) and \( \lambda_2 = 314.48 \text{ nm} \) in a magnetic field of \( 32 \cdot 10^6 \text{ A/m} \) disappeared.

4. Conclusions

The experimental results showed that it is possible to obtain hot plasma during the breakdown of high-pressure gases in short intervals in strong longitudinal magnetic fields to create a source of intense X-ray and ultraviolet radiation. This could be applied in the construction of a pulse-periodic thermonuclear reactor.

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References

[1] Rukhadze A A, Omarova N O, Omarova P Kh, Omarov O A 2017 Applied Physics and Mathematics 5 34–47

[2] Omarov O A, Kurbanishmailov V S, Omarova N O 2012 Physics of electrical breakdown of high-pressure gases Monograph - Makhachkala: CPI of the DSU and INPO URAO 226 p

[3] Al-Khareti F M A, Omarov O A, Omarova N O, Omarova P Kh 2015 VANT. Thermonuclear fusion 38 88–96

[4] Zlatin N A 1971 Physics of rapid processes V. 1 M.: The World 103 p

[5] Artsimovich L A, Lukyanov S Yu 1978 Motion of charged particles in electric and magnetic fields M.: Nauka P 224

[6] Ivanov A A 1977 Physics of strongly nonequilibrium plasma M.: Atomizdat 348 p