Magnetic trap formation during the breakdown of high pressure gases in strong magnetic fields

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Abstract. Formation of hot plasma in strong magnetic fields during the breakdown of high-pressure gases in short gaps was studied experimentally. The breakdown occurs as a result of interaction of monoenergetic electron beam with dense plasma ($n \sim 6 \cdot 10^{22} \text{ m}^{-3}$). As a result of the spark channel formation and its explosive expansion inside the gap, the magnetic field in the anode and cathode regions becomes more intense, while between the electrodes it becomes weaker due to the expansion of the channel plasma. Thus, the axially symmetrical magnetic-mirror-type system is formed, which is similar to the magnetic trap. Formation of this system leads to the reduction of energy losses accompanied by a simultaneous increase in the plasma thermal energy, that is, to a considerable increase in its conductivity and temperature.

Introduction

The progress in studies of the hot plasma confinement in tokamaks contributes not only to the development of fusion physics and technologies, but also to the further practical use of this new energy source. At the same time, there are the alternative confinement systems that are not fully studied, but they may be rather efficient. Searching the efficient and simple energy source is one of the high-demand fields of research [1]. From this point of view, the traps with decreasing magnetic field are very promising [2, 3]. These traps include simple magnetic mirrors [4, 5], their combinations forming the corrugated toroidal magnetic configurations [6–9], as well as the traps with inner conductors surrounded by plasma [10, 11]. One of the main advantages of such traps is their simplicity. They can be used for the efficient confinement of plasma energy in various devices, such as the high-power ECR sources of multiply charged ions, the devices for isotope separation, as well as the high-power plasma-chemical reactors.

The general problem can be formulated as follows: it is necessary to find the optimal configuration ensuring the localized plasma confinement, the highest energy content being in the central region. In this work, the technique is being developed that provides achieving optimal parameters for the high-pressure plasma confinement. 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.

Experimental setup

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 experimental arrangement and techniques used are
described in detail in [12–15]. 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 \( n_0 \sim 10^{14} – 10^{15} \) m\(^{-3}\). Voltage pulses with adjustable amplitude of up to 30 kV and a rise time of \(~10\) 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 \( \Omega \) 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 column was determined using the equation
\[
R(t) = \frac{U(t) - L \frac{dI(t)}{dt}}{I(t)},
\]
where \( L \) is the discharge circuit inductance (\( 5 \cdot 10^{-8} \) H), and \( U(t) \) is the voltage drop across the discharge gap. The external magnetic field was created by means of discharging the capacitor bank through the solenoid, inside which the gap under study was installed. The magnetic field intensity was up to 400 kOe and its period was of the order of 600 \( \mu s \). The discharge radiation was recorded through the side apertures provided in the central solenoid coil. Using the ISP-30 quartz spectrograph and theVFU-1 high-speed photographic camera, the discharge radiation spectrum was recorded, and the intensity of the spectral lines was recorded using the DMP-4 double monochromator in combination with the FEU-29 and FEU-79 photomultipliers. Spectra were processed using the Mathcad computer aided design program.

When the breakdown-creating voltage pulse is applied, a plasma streamer starts propagating from the anode to the cathode at a speed of \(~10^6\) m/s (plasma front propagates in the entire gap volume, plasma density is \( n_e \sim 10^{21} \) m\(^{-3}\)), leading to the initiation of the high-pressure volume glow discharge. As the field between the plasma front and the cathode increases, the cathode spot is formed, from which the thermionic beam starts drifting (with a density of \( n_e \sim 10^{19} \) m\(^{-3}\), energy of \(~5\) keV, and duration of \(~10^{-11}\) s), leading to the formation of a spark channel with a diameter of \( d = 10^{-4}\) m (Figure 1).

![Figure 1. Frame-by-frame photographs taken in the discharge gap (\( E/p \approx 14\) V/(cm Torr); the overvoltage is 65%, anode is in the top, cathode in the bottom): a) frame-by-frame photographs taken in the channel-arc stages of the spark discharge (time is counted from the leading edge of the voltage pulse supplied to the discharge gap); (1) drift of the electron beam through plasma; (2), (3), (4), and (5) transition of the expanding spark channel into the quasi-stationary arc discharge; b) continuous slit scan images.](image)

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 spark 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). This system is a magnetic adiabatic trap, in which the energy losses are reduced and the internal plasma energy increases [16, 17]. An increase in the rate of energy input into the spark channel of the high-pressure discharge results in a considerable
increase in the plasma conductivity and temperature. The studies have shown that the strong plasma-beam interaction occurs in the trap, which results in a considerable increase in the plasma transverse dimensions, as well as in the strong heating of the high-energy electrons captured in the trap.

If the magnetic field induction \( B \) does not depend on time, the electric field is zero \( E = 0 \), there are no collisions, and the scale of the magnetic field variation \( K \) exceeds the Larmor radius \( r_l \), then the following relations are true:

\[
W = \frac{m\nu^2}{2B} = \text{const} \quad \text{and} \quad W_{\text{inf}} = \frac{m\nu^2}{2} = \text{const}.
\]

Since \( W = \frac{m\nu^2}{2} + \frac{m\nu^2}{2} = \frac{m\nu^2}{2} + \mu B \) and \( \nu^2 \geq 0 \), then particles could not penetrate into the region with \( B > W_{\perp}/\mu \) (\( B = W_{\perp}/\mu \) is the stop-point), so the particles with \( W_{\perp}/\mu > B_{\text{max}} \) are not confined. Electrons with the transverse velocities \( \nu_{\perp} \) of the order of the longitudinal ones \( \nu_{||} \) appear in the system. They can be captured in the trap, inside which they are involved in the plasma-beam interaction. This results in a considerable increase in the plasma transverse dimensions, as well as in the strong heating of electrons [14].

As the ohmic resistance decreases to a few tenths of an \( \Omega \), the spark channel plasma forms and, in the course of its time evolution, the high-frequency oscillations of the electric field strength and current occur in the gap \( E = E_0 \exp\left(\frac{-Rt}{2L}\right)\cos(\omega t) \). In the experiment described, the oscillation frequency is \( \omega_{\text{osc}} = \frac{1}{\sqrt{LC}} \sim 10^7 \text{ s}^{-1} \), (where \( L \sim 10^{-8} \text{ H} \), and \( C \sim 10^{-6} \text{ F} \)). The electric field heats the plasma, since the frequency of electron-ion collisions is \( \nu_{ei} \sim 10^{13} \text{ s}^{-1} \gg \omega_{\text{osc}} \sim 10^7 \text{ s}^{-1} \). During the half-period of the electric field oscillations, manifold electron-ion collisions occur that increase the plasma thermal energy.

If the plasma expansion rate is known, the plasma pressure in the discharge column causing the spark channel expansion can be determined using the expression: \( P = k\rho_0\nu^2 \), where \( k \) is a coefficient close to unity, which characterizes the resistance to expansion, and \( \rho_0 \) is the gas density. Using the formula \( P = k\rho_0\nu^2 \), we can estimate the plasma ion density \( n \sim 10^{18} \text{ cm}^{-3} \).

In the longitudinal magnetic field, the plasma expansion is determined by the difference in the gas-dynamic and magnetic pressures, i.e.,

\[
k\rho_0\nu_{||}^2 = k\rho_0\nu^2 + \frac{H^2}{8\pi} - \frac{H_{av}^2}{8\pi} = k\rho_0\nu^2 - \frac{H_{av}^2}{8\pi} \left[ 1 - \left( \frac{H_{av}}{H_0} \right)^2 \right].
\]

Here, \( \nu_{||} \) is the expansion rate in the presence of a magnetic field, \( H_0 \) is the magnetic field at the spark channel boundary, and \( H_{av} \) is the magnetic field averaged over the spark channel plasma. Using equation (1), we can determine the ratio \( H_{av}/H_0 \), which characterizes the field penetration into the spark channel plasma.

\[
\frac{H_{av}}{H_0} = \left[ 1 - \frac{8\pi}{H_0} k\rho_0 \left( \nu^2 - \nu_{||}^2 \right) \right]^{1/2}.
\]

Using the experimental data on \( \nu \) and \( \nu_{||} \), let us determine the ratio \( H_{av}/H_0 \) at \( W = 25\% \). In the absence of the magnetic field in the initial stage of expansion, the expansion rate is \( 2.3 \times 10^5 \text{ cm/s} \), and at \( H = 140 \text{ kOe} \), we obtain \( \nu_{||} = 1.15 \times 10^5 \text{ cm/s} \). Substituting \( \rho_0 = 3 \cdot 1.8 \times 10^{-3} \) into equation (2), we obtain
$H_{av}/H_0 \approx 0.97$, i.e. $H_{av} \approx H_0$. This indicates the rapid field penetration into the plasma of the expanding channel. For comparison, the $H_{av}/H_0$ ratio estimated for the expanding plasma of the cathode spot ($v \sim 10^6$ cm/s) is approximately 0.4–0.5. Thus, the degree of field penetration into the plasma is determined not only by the plasma conductivity, but also by the transverse expansion rate. On the other hand, the higher is the $H_{av}/H_0$ ratio, i.e. the larger is the magnetic field gradient at the plasma boundary, the stronger is the effect of the field on the rate of the transverse plasma transport. The expansion rate is determined by the rate of energy input into the spark channel. If the energy input rate is increased, the $H_{av}/H_0$ ratio will also be increased, and the specific power, conductivity, and plasma temperature will accordingly increase.

Conclusions
(i) In the strong external longitudinal magnetic field, as well as in the channel radial magnetic self-field, after the formation of the ionized spark channel and the beginning of its explosive expansion, the magnetic trap is naturally formed, in which the magnetic field strength between the electrodes is weaker, and it increases towards the anode and the cathode as a result of the spark channel plasma expansion.
(ii) The external longitudinal magnetic field reduces the rate of the spark channel expansion, the intensity of the integrated transverse radiation and the radial ambipolar diffusion.

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