Stable Plasma Column in a Longitudinal Magnetic Field

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The results of the experimental study of a pulse discharge between two electrodes in a straight tube in the presence of a longitudinal magnetic field are presented in this paper. The discharge starts approximately along the tube axis and gradually expands. When the strengths of the longitudinal magnetic field and the magnetic field of the current at the plasma boundary are related in certain definite ways the discharge column remains stable and does not reach the tube walls. For strong currents, when the field of the current is comparable to the longitudinal field, the plasma column fills the whole tube cross section and becomes unstable.

To obtain a high temperature in a discharge without electrodes it is essential in the first place to ensure the macroscopic stability of the plasma column. In the experiments described, therefore, we have studied pulsed deuterium discharges in a straight tube, with electrodes in the presence of a longitudinal magnetic field.

The maximum current varied from 3000 to 300,000 amp. The duration of the first half-cycle of the current ranged from 300 to 1800 μsec. The magnetic field in the same direction as the current could be adjusted from 0 to 27,000 gauss. The initial deuterium pressure in the experiments varied from 0.005 to 5 mm Hg.

The amplitude of the current through the gas and the longitudinal magnetic field could be varied independently in different experiments. Thus, for a wide range of absolute values of the current through the gas, the ratio of the longitudinal magnetic field $H_0$ to the magnetic field of the current $H_\phi$ could be varied from 1 to 10.

EXPERIMENTAL EQUIPMENT

Investigations of the stable plasma column were carried out with several units very similar in construction, size and characteristics of the feeding circuits. A schematic view of such a unit is shown in Fig. 1.

The discharge tube is a porcelain or glass tube of 18 to 23 cm diameter and 80 cm high. The faces of the tube are covered by porcelain plates on which copper or stainless steel electrodes are mounted. In the experiments described the following electrodes were used: flat electrodes 9 cm and 17 cm in diameter, and hemispherical electrodes 4 cm in diameter. The distance between the electrodes in all the experiments was ~70 cm, unless otherwise stated.

The discharge tube was surrounded by a 5 mm thick coaxial stainless steel return conductor whose stabilizing effect should be negligible. The longitudinal magnetic field in the discharge tube was excited by a coil through which a $C_2$ capacitor bank of 10,000

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Figure 1. General diagram of the experimental equipment:
1. coaxial return conductor; 2. porcelain or glass tube; 3. slot for photographing; 4. spherical spark gap; 5. trigger circuit; 6. from control board; 7. synchronization circuit; 8. trigger circuit; 9. voltage divider; 10. to oscillograph; 11. belts for measuring the current distribution; 12. turns for measuring the distribution of the longitudinal magnetic field; 13. coil producing the longitudinal magnetic field; 14. copper or stainless steel electrodes.

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to 100,000 μF was discharged. The pulse current in the tube was produced by the discharge of the capacitor bank (800 to 6800 μF) through a spherical spark gap.

The C₁ and C₂ banks were made up of pulse capacitors of the IM–3–100 type each with a 100 μF capacity and a charge voltage of 3 kV.† The amplitude of the discharge current was adjusted from 3 to 300 kA and the duration of the first current half-wave from 300 to 1800 μsec by varying the capacitor bank voltage and by the insertion of an additional inductance L into the circuit.

The C₁ and C₂ banks worked jointly in the following way. When the current in the coil reached a maximum, the synchronization circuit triggered the spark gap in the C₁ circuit, producing a discharge through the gas. The discharge circuit oscillation period was chosen to be much less than that of the circuit producing the longitudinal magnetic field. Thus, the discharge occurred in an almost constant magnetic field. The strength of the longitudinal magnetic field could be raised to 27,000 gauss.

The discharge was investigated in deuterium (at pressures p from 0.005 to 5 mm Hg) and in argon. The tube was filled with deuterium through a palladium filter ensuring the appropriate purity of the gas. After the discharge the tube was evacuated to a pressure of 1–2×10⁻⁵ mm Hg by an oil diffusion pump with a trap cooled with liquid nitrogen.

PROCEDURE AND RESULTS

For each of the experimental conditions chosen the following parameters were measured: (a) the total discharge current, (b) the voltage between the electrodes,
(c) the current in the concentric zones of the tube cross section and (d) the mean value of the longitudinal magnetic field in the tube. In addition, the plasma column was photographed by a high-speed camera, the discharge spectrum was also photographed and the time variation of the intensity of separate spectral lines was recorded.

The discharge current was measured by a Rogovsky belt, the voltage from it being integrated by an RC circuit. A low-resistance divider, whose self-inductance was much less than its effective resistance, was connected between the electrodes, in parallel with the discharge column. In order to record the current, the voltage, and other characteristics of the discharge, a double-beam pulse oscilloscope of OK-17M type was employed.

Oscillograms of the voltage between the electrodes and of the discharge current are shown in Fig. 2. The discharge current pulse is similar in form to a sine curve. Its duration and magnitude vary scarcely at all with change in $H_0$ and $p$. This is explained by the fact that the total impedance of the discharge circuit is much greater than the discharge resistance. The oscillograms of the voltage show that the inductive component of the discharge impedance is considerably less than its resistance.

Figure 3 shows that the voltage between the electrodes has two typical stages. At first it is approximately constant; we call this the “plateau” stage. Then the voltage rises and a very transient voltage is observed. The time prior to the beginning of the
second stage ("plateau" duration) is inversely proportional to the rate of the current increase. This time rises as the longitudinal magnetic field increases (Fig. 4). At rather large values of \( H_0 \) the "plateau" is observed all the time the current flows through the gas (Fig. 2).

The voltage between the electrodes at the moment when the discharge current reaches its maximum increases linearly with the amplitude of the current and depends little on the initial pressure \( p \) and the magnetic field \( H_0 \). The size of the electrodes and the material of which they are made influence the magnitude of voltage between them.

Two procedures were used for studying the configuration of the plasma column: (1) the transverse distribution of the current in the plasma column was
measured with Rogovsky concentric belts, and (2) the plasma column was photographed by a high-speed camera. The Rogovsky belts placed in quartz tubes 8 mm in diameter were inserted inside the tube. The equal-sensitivity of the belts made it possible to balance one belt against another in order to measure directly the current in each of the three concentric zones between the belts. The arrangement and the sizes of the belts are given in Fig. 5.

Figure 6 presents oscillograms of the current in the central and near-wall tube zone. For the same zone these oscillograms have the same current and time scales. At the initial value of magnetic field ($H_0 = 27,000$ gauss) the current in the near-wall zone is very small; with the decrease in $H_0$ the current in the near-wall zone increases, but in the central part it drops. Figures 7 and 8 present the results of the analysis of such oscillograms.

When $H_0$ has the value 15,000 gauss, the density of the current in the near-wall zone is negligible, while the current density in the central zone is 15 times larger than the mean current density at the beginning of the process, and 7 or 8 times larger at the end of the process. When the intensity of the magnetic field is equal to 5000 gauss, the current density distribution becomes more regular (Fig. 7). With a still smaller ratio of $H_0$ to $H_b$, when the "plateau" of the voltage is sharply pronounced, the current distribution at the moment corresponding to the end of the "plateau" changes appreciably: the current in the central zone drops; at the extreme it increases sharply and there appear strong oscillations corresponding to the redistribution of the current over the tube cross section (Fig. 8).

Thus, the measurements of the current density distribution over the tube cross section have shown that under definite conditions a discharge may be realized in which the current through the near-wall zone is negligible ($j < 1$ amp/cm$^2$), i.e., the plasma column interacts weakly with the tube walls and exists as long as the current passes through the gas.

For such discharges the imaginary radius $a$ of the current column was plotted as a function of time. This "current" radius was defined as follows: a quadratic dependence of current density on the radius $j = A(1 - Bx^2)$ was taken, and the constants $A$ and $B$ were calculated assuming that the entire current inside the internal and central zones coincided with the measured values. The current in the near-wall zone was neglected (Fig. 9).

Figures 10 and 11(a) show the dependence of "current" radius on time. The oscillograms corresponding to the first half-period of the current (300 or 1600 µsec) were treated. For all the operating conditions some increase in the "current" radius at the beginning of the process is typical. Then the radius remains almost invariable until the current vanishes.

The change of the luminous plasma column width with time was photographed simultaneously with the measuring of the current distribution. For this purpose a narrow cross slot was made in the middle of the coil producing the longitudinal magnetic field (Fig. 1). Such photographs for discharges with the first half-period equal to 300 or 1600 µsec were treated. For all the operating conditions some increase in the "current" radius at the beginning of the process is typical. Then the radius remains almost invariable until the current vanishes.

In the streak photographs of the plasma column luminous sinusoidal stripes attract the attention. The amplitude of oscillation of the stripes increases with the rise of the current in the discharge and decreases with the rise of the longitudinal magnetic field. During the first half-period their frequency decreases, which is much more visible in the photographs of a discharge in argon (two lower photographs on Fig. 11(b)). The explanation of these regular motions requires further investigation. However, it is possible to state that they are not associated with the distortion of the basic part of the current through the gas.
The interior wall of the discharge tube is denoted by white lines at the edges of the photograph. From the photographs of the discharge, it is possible to plot the dependence of the plasma column "luminous" radius on the longitudinal magnetic field and on the pressure.

The dependence of the plasma column "current" and "luminous" radii on the longitudinal magnetic field (Fig. 12) shows that the "luminous" radius exceeds almost twice the "current" radius (according to the above-described procedure of analysis), but the laws of their variation in time are similar. The curves plotted for various electrodes differ slightly. For electrodes with a 17 cm diameter there has been observed an increase of the "current" radius with the rise of the magnetic field. It should be noticed that the "current" radius for electrodes with a diameter of 4 cm cannot be less than 2 cm on account of the large size of the central measuring belt.

The radius of the plasma column increases as the longitudinal magnetic field decreases and as the discharge current or the distance between the electrodes increases. The curves in Fig. 13 show that the radius of the plasma column depends slightly on the pressure. The plasma column at the pressure of 5 mm Hg occupies the whole tube, and is unstable. The oscillograms show in this case a very transient voltage. It should be noticed that for such a discharge \( \omega_i^2 \tau_i^2 < 1 \), where \( \omega_i \) is the Larmor ion frequency and \( \tau_i \) is the ion–electron collision time.

The changes caused by the discharge in the distribution of the longitudinal magnetic field over the tube...
the coil producing the longitudinal magnetic field were balanced against the measuring turns. The sensitivity of the compensating turns was chosen so that in the absence of a discharge, the signal from unit magnetic field linking both loops should be as small as possible. Since the external resistance of the magnetic coil circuit is small in comparison with the inductive impedance of the coil, the magnetic flux in it remains constant during the discharge, and hence the compensating turns cannot record the magnetic field alterations inside the discharge. The emf induced in the turns was integrated by the RC circuit.

For all discharges there was observed an increase in the longitudinal magnetic flux within the discharge. The oscillograms of the magnetic flux alterations are presented in Fig. 14. The analysis of such oscillograms (Fig. 15) shows that the gas pressure in this case is considerably lower than the magnetic pressure.

In discharges separated from the walls, when \( H_0 \gg H_\phi \), the increase in the longitudinal magnetic field within the discharge is small in comparison with its nonexcited value. Therefore, the measurements under these conditions are only of a qualitative nature. They show that the equilibrium of the magnetic tensions is considerably disturbed only at small currents when even at low temperatures (10–20 ev) the gas pressure becomes comparable with the magnetic field pressure.

A study of the nature of the spectrum in the visible region was carried out for various discharges throughout the entire current pulse; the time variation of separate lines of this spectrum was also studied. The discharge spectrum was photographed by a ISP-51 spectrograph accommodating glass optics. The time variation of separate spectral lines was investigated by a UM-2 monochromator provided with a FEU-19 photomultiplier. To protect the photomultiplier from the dispersed magnetic field the monochromator with the photomultiplier is placed in a metal encasement. The signal received from the photomultiplier was amplified, and recorded by an oscilloscope.

The radiation was observed through a small hole...
Figure 14. Examples of current oscillograms (upper trace) and measurement of magnetic flux within a discharge (lower trace). The upper oscillogram corresponds to a system with $p = 0.2 \text{ mm Hg}$, $l_m = 90 \text{ ka}$, $H_0 = 4500 \text{ gauss}$, and the lower with $p = 1 \text{ mm Hg}$, $l_m = 180 \text{ ka}$, $H_0 = 4500 \text{ gauss}$.

Figure 15. Time variation of the increment of the magnetic flux within the discharge measured experimentally and the value $\Delta \Phi / 2H_0$ calculated for conditions corresponding to an increment of the magnetic flux that is at magnetic pressure balance. Conditions: $p = 0.2 \text{ mm Hg}$, $l_m = 1800 \text{ ka}$, $H_0 = 4500 \text{ gauss}$ (25 mm diameter) in the magnetic coil, located halfway between the electrodes.

In addition to the Balmer lines there were observed, in the spectra of some discharges under investigation, lines of the atoms and ions of the wall and electrode materials. Thus, for example, the spectra of the discharges which occur without a longitudinal magnetic field, or at a comparatively weak magnetic field, involve the Si$^{1+}$ lines 4128 Å, 4130 Å and several others.

Figure 16. Oscillograms of the time variation of the $D_3$ intensity and the total discharge current for $p = 0.01 \text{ mm Hg}$, $l_m = 45 \text{ ka}$ and various magnetic fields. Oscillograms (c), (d) and (e) are obtained with greater amplification on the photomultiplier than (a) and (b). The field strengths $H_0$ are: (a) 0, (b) 5, (c) 5, (d) 10, (e) 15 kilogauss.

Figure 16 shows the oscillograms of the photomultiplier signals induced by the radiation of the Balmer line $D_3$ from the discharge. These oscillograms show a decrease in the intensity of the Balmer lines after the superposition of the magnetic field. This decrease is sharper for a larger field.

The oscillograms in Fig. 17 convincingly confirm the existence of a stable discharge. They express the character of the time variation of the radiation intensity of the silicon lines (4128 Å and 4130 Å), and
Figure 17. Oscillograms of the time variation of the Si line at 4128 Å and the total current for \( p = 0.01 \) mm Hg, \( I_m = 45 \) kA and various magnetic fields \( H_0 \): (a) 0, (b) 5, (c) 7.5, (d) 10, (e) 12, (f) 15 kilogauss

evidence a significant relaxation of the interaction of the discharge plasma with the tube walls when the longitudinal magnetic field is sufficiently large and the radius of the plasma column is smaller than the interior radius of the discharge tube. All the photomultiplier signal oscillograms presented are synchronized with the discharge current trace.

**DISCUSSION OF RESULTS**

The measurements of the current density distribution over the cross section of the discharge column and the streak photographs show that under experimental conditions the discharge starts near the tube axis. This fact is observed for all the values of the longitudinal magnetic field and very often for \( H_0 = 0 \). This is possibly associated with the configuration of the electric fields before the breakdown. Since the rate of the current increase is small and the plasma resistance at these discharge stages is high \((R \gg \omega L)\), the discharge develops in the central region where the conductivity is much higher. The original discharge channel expands but does not reach the walls and remains stable when \( H_0 \) is large enough. Investigation of the dependence of the radius of the plasma column on the longitudinal magnetic field was described in Ref. 1.

The radius of the stable plasma column as shown in Ref. 2 must satisfy the condition

\[
a \geq \frac{\lambda}{2n H_0} J_0
\]

where \( \lambda \) is the wavelength of excited instability, \( H_0 \) is the intensity of the field at the discharge column boundary and \( H_0 \) is the intensity of the longitudinal magnetic field. Numerical comparison of the radii obtained experimentally and those calculated by means of the formula

\[
a = \frac{l J_0}{\pi H_0}
\]

shows that Eq. (1) is correct if \( \lambda \) is taken as \( 2l \), where \( l \) is the electrode separation—70 or 135 cm.

The data presented (Fig. 12) show that the decrease in the intensity of the longitudinal magnetic field if \( H_0 < 15,000 \) gauss leads only to an increase in the plasma column radius but not to instability. One of the possible explanations of such a discharge behaviour may lie in the following mechanism: after the start in the narrow discharge channel, the current density increases with time and may turn out to be considerably larger than the current density allowed by the stability conditions (1) for the discharge column radius. In this case instability is developed in the narrow column and its wavelengths will be smaller, the poorer the fulfilment of condition (1). Macroscopic motions of the unstable column lead to a partial ionization of the neutral gas enveloping the plasma column and, consequently, to an expansion of the conducting region through which the current flows. Such a process will take place until the current density becomes stable, equal to \( j_0 \), the value \( H_0 \) on the boundary drops and conditions are created for the existence of a stable plasma column.

We do not have at our disposal sufficient data to evaluate the time of existence of the stable plasma column. In comparing the data presented in Fig. 12, one can see that the stable plasma column in experiments with a duration of the first half-cycle of 1600 μsec has a larger radius than in experiments with a duration of the first half-cycle of 300 μsec, although all the other conditions are the same. It may be assumed that diffusion phenomena become essential when the period is increased. However, it may be
possible that the diffusion phenomena affect the process during a shorter period of time, and the stable column radius may be defined by the ratio of the diffusion rate to the charged particle drift.

In experiments with narrow electrodes, when the plasma column radius exceeds the radius of the electrode, the voltage across the gap increases and becomes transient. But this is not associated with instability of the discharge column, as no chaotic redistribution of the current density over the cross section is observed. This may be associated with the fact that in this case the electrons near the electrodes have to travel across the magnetic field.

The conductivity of the plasma column in the magnetic field is anisotropic. In such a plasma the current flows along a spiral line intensifying the magnetic field within the plasma column.

Calculations show that the increment of magnetic flux caused by the anisotropy of conductivity,

\[
\Delta \phi = \frac{\pi a^2 H_0^2}{4H_0}
\]

can balance only half of the pressure produced by the field \(H_0\).

In experiments with currents of 100 ka or more there is always observed an equality between the magnetic pressures of the field of the current and of the increased longitudinal magnetic field within the plasma column.

If we assume that the plasma column expands, a "diamagnetic" effect, i.e., a magnetic field repulsion effect, must be observed. The expansion of the ionization region resulting from the mechanism described above does not require a repulsion of the field lines. On the contrary, the expansion of the ionization region might take place simultaneously with the constriction of the plasma column and with an increase of the magnetic field intensity within it, in order to satisfy the requirements of equality of the magnetic pressures.

Measurements of the voltage between the electrodes and of the current through the gas provide all the data for the evaluation of the plasma conductivity and the degree of ionization.

By excluding the inductance component from the measured value of the voltage between the electrodes, it is possible to determine the value of \(E\), the intensity of the electric field in the plasma. The evaluation of the plasma conductivity in stable regimes shows that, at the moment of maximum current, in the central zone it reaches the value of 3 to 5 \(10^{14}\) cm⁻³, while in the internal zone it reaches only 1 \(10^{14}\) cm⁻³. At small values of \(H_0/H_0\) the conductivity increases only until the discharge column touches the tube walls. After this moment the conductivity in the central zone decreases to values close to the mean value over the discharge cross section.

It follows from the evaluation of the energy transferred to the electrodes that the plasma temperature cannot exceed 50 ev. Therefore, if the conductivity is of the order of 5 \(10^{14}\) cm⁻³, the degree of gas ionization must exceed 20 per cent. This also agrees with the measurements of the \(D\phi\) line intensity with time, which decreased with increase in the magnetic field, and had a pronounced maximum in the zero region of the current (Fig. 16).

**CONCLUSIONS**

The following conclusions may be made, based on the experimental material:

1. In straight gas discharge tubes when the distance between the electrodes exceeds the tube diameter appreciably and also in the absence of a coaxial damping conductor, the discharge column in a longitudinal magnetic field can be stable for more than a thousand microseconds.

2. After the breakdown, the region occupied by the discharge expands and the rate of this expansion increases with increase in the derivative of the current and decreases with increase in the intensity of the longitudinal magnetic field.

3. At large \(H_0/H_0\) ratios, when the relation \(H_0/H_0 > \lambda/2\pi a\) is satisfied, the discharge column does not reach the walls and remains stable while the current flows.

4. If the condition in item 3 is not satisfied, the discharge fills the whole tube volume and the stability fails.

5. The ionization in the stable plasma column exceeds 20 per cent.

6. The longitudinal field within the plasma column increases up to the value sufficient to ensure equality in the magnetic pressures (neglecting the insignificant pressure of the plasma heated to 10–100 ev).

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