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STUDY OF A TOROIDAL DISCHARGE IN A RAPIDLY VARYING LONGITUDINAL MAGNETIC FIELD

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Unlike the constant magnetic field used for stabilizing the current in work (^{1}), a variable longitudinal field can be effectively used for confinement and heating of plasma, and not only for imparting stability to it.

For a rough estimate of the rate of increase of the longitudinal magnetic field at which the effect of its variation becomes substantial, one may consider a plasma cord produced by a longitudinal field alone, as was done in work (^{2}). In such a cord the plasma pressure p is confined by an azimuthal current I_φ, which weakens the field inside the cord by an amount $\Delta H = \sqrt{\overline{H_i^2} - H^2}$, where H is the field outside, H_i is the field inside, and the bar denotes averaging over the cross section of the cord. From the condition of pressure balance,

$$\frac{(H+\Delta H)^2}{8\pi} + p = \frac{H^2}{8\pi}; \qquad \Delta H = -H \pm \sqrt{H^2 - 8\pi p} \simeq$$

$$\simeq \begin{cases} -\beta H/2, \\ -2H + \beta H/2, \end{cases} \qquad \text{if } \beta = \frac{8\pi p}{H^2} \ll 1,$$

i.e., equilibrium can be realized both in a field of one direction, when the plasma pressure is confined by a small difference between the fields inside and outside, and in the case when inside the plasma cord the field is almost equal to the external one but is directed opposite to it, and the pressures of these fields practically balance each other.

To maintain the current I_φ, an increase is required in the flux of the longitudinal magnetic field inside the cord, $\Phi = \pi a^2 (H + \Delta H) \simeq \pm \pi a^2 H$. Since in the two cases of equilibrium this flux has different signs, it follows that, in the case of fields directed alike,

$$\Delta H \simeq -\frac{\beta}{2} H \simeq \frac{4\pi}{c} I_\varphi \simeq -\frac{\sigma}{c^2}\frac{d\Phi}{dt} = -s\left(\frac{dH}{dt} + \frac{2H}{a}\frac{da}{dt}\right), \tag{1}$$

Fig. 1

Figure 1: Fig. 1

where it is assumed that the current I_φ flows in a layer of thickness $\delta \sim a/2$; σ is the plasma conductivity; $s = \pi a^2 \sigma / c^2$ is the "skin time." Thus, in a constant field ($dH/dt = 0$) the plasma must expand with velocity $da/dt \simeq \beta a / 4s$, while for confinement or compression of the plasma ($da/dt \leq 0$) the field must be increased at a rate $dH/dt \geq \beta H / 2s$.

In the case of oppositely directed fields,

$$\Delta H \simeq -2H \simeq s \left(\frac{dH}{dt} + \frac{2H}{a} \frac{da}{dt} \right), \tag{2}$$

i.e., in a constant (or slowly varying) field compression will occur with velocity $da/dt = -a/s$, and the total compression time will be

$$t_{\text{comp}} = \frac{\pi\sigma}{c^2} \int_0^{a_0} a\, da = \frac{\pi \sigma a_0^2}{2c^2} = \frac{s_0}{2}. \tag{3}$$

A state with opposing magnetic fields can be obtained, for example, when the longitudinal field outside the plasma begins to weaken rapidly. The weakening of the field inside the plasma lags because of the azimuthal currents arising in it, as was shown in work ([3]), and the plasma tends to expand. If the plasma is restrained from expanding by the walls of the chamber or by the field of the longitudinal current, then, according to equation (1), the excess field inside will be

Fig. 1. Oscillograms: voltage around the torus *(a)*, discharge current *(b)*, current in the longitudinal-field winding *(c)*, self-field of the discharge current 3 cm from the outer wall of the chamber *(d)*. Streak photographs of the glow of the side *(d)* and upper *(e)* transverse slits in the chamber. Change in the radius of the discharge column, calculated from equations (1) and (2) for $\sigma_\perp = 0.5 \cdot 10^{14}$ CGSE *(zh)*, and the field inside the chamber *(z)*. The points in Fig. 1 *zh* indicate the places where H_I reaches its maximum in the distribution over the chamber cross section (i.e., the current density is approximately one half of the average). Discharge in Ar at $p = 0.005$ mm Hg, $E_{\text{init.}} = 1$ V/cm.

$$\Delta H = s_0\, dH/dt. \tag{4}$$

If the rate of change of the external field is sufficiently large, so that the pressure of the excess field inside is substantially greater than the plasma pressure, i.e. $dH/dt \gg \frac{1}{s_0}\sqrt{8\pi p}$, then, when the external field changes direction and reaches the value $-\Delta H/2$, the field inside will be $+\Delta H/2$, as a result of which,

Figure 2

Figure 2: Figure 2

even if further change of the external field ceases, compression will begin according to equation (2).

The experiments were carried out in a toroidal discharge chamber whose copper casing, with torus diameter 40 cm and aperture diameter 16 cm, had two transverse and one longitudinal joint. Into the casing was inserted a chamber made of 48 rings of 0.2 mm stainless steel separated by Teflon spacers. The chamber was pumped down to a pressure of $\sim 1 \cdot 10^{-5}$ mm Hg. The operating pressure of deuterium or argon was varied from 0.004 to 0.02 mm Hg. The discharge current reached 50 kA at an initial voltage around the torus of 360 V and a half-period duration of 250 μsec. In the chamber there could be produced a longitudinal magnetic field of up to 4000 oersted, practically constant during the discharge, and a field varying rapidly up to ± 6000 oersted relative to the level of the constant field, at a rate of up to 10^8 oersted/sec.

Fig. 2. Distribution over the cross section of the chamber of the longitudinal magnetic field H_z, of the intrinsic field of the discharge current H_1, and of the current density j_z: **a**—in the case of longitudinal fields of the same direction (the instant t_1 in Fig. 1) and **b**—in the case of oppositely directed fields (the instant t_3 in Fig. 1). Discharge in D_2 at $p = 0.01$ mm Hg, $E_{\text{init}} = 3$ V/cm, $I_{\max} = 36$ kA, $H_0 = 800$ oersted, $H_{\max} = 2400$ oersted.

The discharge in the chamber was photographed with a high-speed camera simultaneously through two transverse slits, from above and from the side. In addition, magnetic probes were used to measure the distribution over the chamber cross section of the longitudinal magnetic field and of the intrinsic field of the current. Oscillograms and photographs are given in Figs. 1 and 2.

The detachment of the cord from the walls by the rapidly increasing field, shown in Fig. 2a and corresponding to the instant t_1 in Fig. 1, is maintained for almost the entire half-period of the additional field if the longitudinal current does not exceed values for which the Shafranov-Kruskal stability conditions are satisfied, and is rapidly destroyed if the stability conditions are not satisfied. In the time between t_2 and t_4, a configuration with oppositely directed fields is formed (Fig. 2b), and a sharp compression of the cord occurs, accompanied—

···accompanied by a drop in current and an increase in the loop voltage owing to an increase in the inductance of the cord.

According to the current and voltage oscillograms, the conductivity by the moment at which compression begins in opposing fields is $1 \div 2 \cdot 10^{14}$ CGSE. The amplitude of the opposing field, according to probe measurements, is approximately 800 oersteds at $dH/dt = 5 \cdot 10^7$ oersteds/sec, which is in good agreement with formula (4). From the velocity of motion of the front of field interpenetration, $da/dt \sim 2 \cdot 10^5$ cm/sec, and the time of field reversal at a given point ($\sim 2\mu$sec), one may estimate that the width of the region of field reversal does not exceed ~ 1 cm. Thus, azimuthal currents arise in it with density $j = I_\varphi/\delta = c\Delta H/4\pi\delta \sim 2000$ A/cm^2. This explains the strong, sharply bounded glow observed in the streak photographs (Fig. 1e). However, even a sharp increase in the rate of Joule heat input into the plasma, corresponding to such current densities, does not lead in our experiments to an increase in conductivity. Indeed, the lifetime of the opposing field in our experiments is from 10 to 25 μsec, which corresponds exactly, according to formula (3), to the conductivity observed at the beginning of compression. Equally low values of conductivity are also observed when compression is by a rising field. Apparently, this is connected with insufficient cleanliness of the discharge chamber.

In the process of formation of a configuration with opposing fields, the plasma should gather into a hollow cylindrical layer in the region where the longitudinal field passes through zero. The pressure in this region should be $p \cong H^2/8\pi$. On all sides of it there is an increasing magnetic field, and in the presence of a longitudinal current a strong twisting of the field lines is obtained, for which the Suydam stability criterion[4] is satisfied.

In addition, a large amount of energy is released in the region occupied by the plasma. The total amount of Joule heat released per unit length of the cord when the opposing field $-H$, initially present in the region with radius a_0, disappears, and with a constant external field $+H$, is

$$Q_\mathrm{J} = -\frac{1}{c}\int_0^{t_\mathrm{comp}} I_\varphi \frac{d\Phi}{dt}\,dt = \frac{2H}{4\pi}\int_{-\Phi_0}^{0} d\Phi = 4\frac{H^2}{8\pi}\pi a_0^2,$$

where only the time during which this heat is released depends on the conductivity, while the total amount of it remains unchanged. The power released in the plasma in this process considerably exceeds the power released by the longitudinal current, which can be stabilized by the same field H; it can be increased still further by compression of the plasma.

In contrast to the experiments of Kolb[5] and installations of the "Scylla" type, the lifetime of the opposing field in our experiments is determined by the conductivity of the plasma along, rather than across, the magnetic field because of the presence of the discharge current' s own field. This same field should hinder the flow of plasma in the layer in the direction of the outer wall of the torus, which could lead to interruption of the azimuthal currents.

For investigation of the stability and heating of the plasma in such a regime, it is necessary to prolong it, which can be achieved by increasing the plasma conductivity through a substantial improvement in the cleanliness of the discharge chamber, or by significantly increasing the amplitude and the initial rate of change of the longitudinal field.

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