# THE TRANSPORT OF PLASMA CLUSTERS WITH THE HELP OF TWO-DIMENSIONAL MULTIPOLE MAGNETIC FIELDS

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**ABSTRACT:** The transport of plasma clusters was experimentally investigated using two-dimensional multipole fields with a multipolarity index of 2s, equal to 4, 6, 8, and 12. It was found that when 2s = 4 the running losses are independent of the magnetic field strength and distance from the plasma gun over a wide range of values. On passing to the case in which 2s = 12, the running losses decrease as the field and distance from the gun increases, all other conditions being equal, the cluster transport occurs with smaller losses. For fairly large twelve-pole fields there are virtually no plasma losses to a distance of 65 cm from the gun.

This paper develops the treatment presented in [1] where it was established that the portions of the plasma cluster close to the axis are transported with small losses when a two-dimensional quadrupole field is employed. We investigated the general losses from a cluster in the course of its motion in a multipole field. These investigations are of physical as well as of practical interest since the behavior of a plasma in fields exhibiting acute-angled geometry has scarcely been investigated either theoretically (owing to the difficulties associated with the nonconservation of the adiabatic invariant) or experimentally. Experiments to the present have been chiefly concerned with the behavior of a plasma in three-dimensional axisymmetric quadrupole fields—antimirror machines (see, for example, [2]).

In what follows we investigate the behavior of plasma clusters injected along the axis of two-dimensional magnetic fields—both quadrupole fields and fields of higher degrees of multipolarity—up to a twelve-pole system.

**§1. Description of the apparatus and methods of measurement.** The work was carried out on the apparatus described in [1]. Plasma clusters were generated by a spark gun [3] and subsequently moved in an evacuated glass pipe.

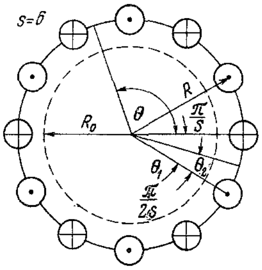


Fig. 1. Diagram of the apparatus producing the magnetic field.

A plane shielded probe with a collector area of 0.17 $cm^2$ was used for local measurements of the plasma parameters (density and flow). To measure the plasma flow over the entire cross section of the tube in which the plasma cluster moved, a similar probe was employed with a collector having the form of a semicircle with a diameter virtually equal to the inside diameter of the tube.

We introduce the following symbols to describe the parameters of the channeling field: R is the radius of the cylinder on which the straight current-carrying conductors creating the magnetic field are situated (Fig. 1), $R_0$ is the inner radius of the tube in which the cluster moves; 2s is the number of conductors creating the field (the multipolarity index); z, r, and θ are the cylindrical coordinates (with the plasma gun situated at the point with coordinates (0, 0, 0); the values of the characteristic angles $\theta_1$ and $\theta_2$ are clear from Fig. 1.

It is well known that the field in such a system is given by (see, for example, [4])

$$H_r = \frac{0.4Is}{R} \frac{\beta^{s-1}(1+\beta^{2s})\sin s\theta}{(1+\beta^{2s})^2 - 4\beta^2\cos^2 s\theta},$$

$$H_\theta = \frac{0.4Is}{R} \frac{\beta^{s-1}(1-\beta^{2s})\cos s\theta}{(1+\beta^{2s})^2 - 4\beta^2\cos^2 s\theta} \quad \left(\beta = \frac{r}{R}\right). \tag{1.1}$$

Here H is in oersteds, I is in amps, and r and R are in centimeters.

In the described experiments $2R_0$ = 7.7 cm, 2R = 9.8 cm (with the exception of the one specifically stipulated case in which 2R = = 15 cm); 2s is equal to 4, 6, 8, and 12. The maximum strength of the current employed was 2.8 · $10^4$ A.

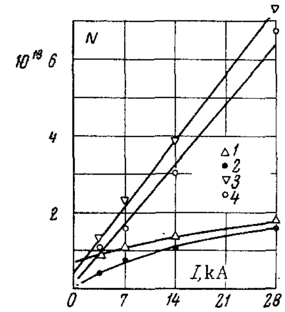


Fig. 2. The amount of plasma $N_L$ passing through 1 $cm^2$ in the region close to the axis as a function of a quadrupole (1 and 2) and twelve-pole (3 and 4) field as two distances from the gun z = 15 cm (1 and 3) and z = 65 cm (2 and 4).

For the sake of convenience and clarity the cable gives the values

$$H_r(R_0) = H_1, \quad [\partial H / \partial r]_{R_0} = H_1', \; H_r(1/2\ R_0) = H_2,$$

$$Q^* = 2s/H_r(R_0),\; H^\theta = [\partial H_\theta/\partial r]_{R_0},$$

for the field parameters for a current of I = $10^4$ A, which does not impair generality since the current occurs linearly in the formulas for the field.

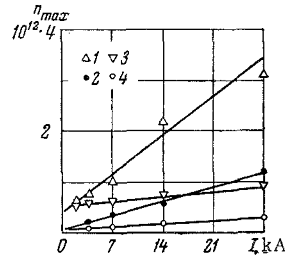


Fig. 3. The maximum plasma density in the axial region as a function of a quadrupole magnetic field (1 and 2) and a twelve-pole magnetic field (3 and 4) for two distances from the gun z = 15 cm (1 and 3) and z = 65 cm (2 and 4).

It is clear both from the formulas and the table that as the degree of field multipolarity increases, the field increasingly concentrates near the conductors, leaving an ever greater virtually field-free region close to the axis, since the field for small $\beta$ decreases as $\beta^{s-1}$ as the radius decreases.

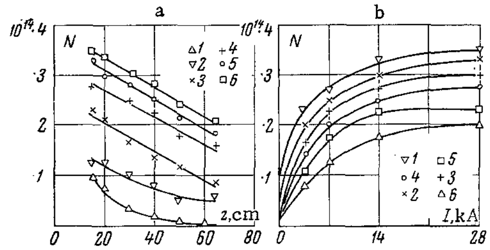


Fig. 4. (a) Variation of the total number of plasma particles (2R = 9.8 cm) as the distance from the gun increases for various values of a quadrupole magnetic field; values of I: 1) 0, 2) 1.4, 3) 2.8, 4) 7.0, 5) 14.0, 6) 28.0 kA. (b) Variation of the total number of plasma particles passing through the tube cross section (2R = 9.8) as the quadrupole magnetic field increases; values of z: 1) 15, 2) 20, 3) 30, 4) 40, 5) 50, 6) 65 cm.

It follows from this that the plasma losses associated with the nonconservation of the adiabatic invariant* should increase sharply for higher indices of multipolarity (see, for example, [5, 6]).

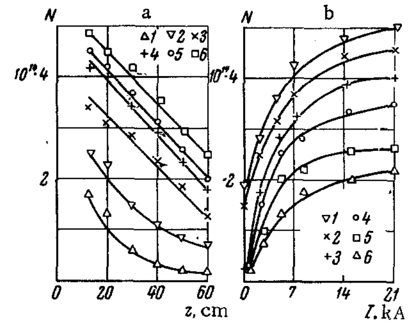


Fig. 5. (a) Change in the total number of plasma particles (2R = 15 cm) as the distance from the gun increases for various values of a quadrupole magnetic field; values of I: 1) 0, 2) 1.4, 3) 2.8, 4) 7.0, 5) 14.0, 6) 28.0 kA. (b) Change in the total number of plasma particles passing through tube cross sections (2R = 15 cm) with an increase in octopole magnetic field; values of z: 1) 14, 2) 20, 3) 30, 4) 40, 5) 50, 6) 65 cm.

**§2. Results and discussion of the experiments.** Both in the quadrupole case (2s = 4) and in the twelve-pole case (2s = 12) the quantity of plasma passing through an area of 1 $cm^2$ in the region close to the axis, $N_L = N_L(z, I)$, as measured by the local probe, increases as the magnetic field increases (Fig. 2). When the fields are large enough, there are practically no losses from the region close to the axis. The magnetic field strength is given in terms of the values of the current flowing through the conductors which produce the multipole fields.

The maximum plasma density in the cluster $n_{max} = n_{max}(z, I)$ also increases with the field (Fig. 3). As the distance from the gun increases, the density naturally decreases since the plasma flows out along the field axis.

The total number of plasma particles passing through the total tube cross section for a current I at a distance z from the gun is denoted by N = N(z, I). The function N(z, I) for the case in which 2s = 4 differs considerably from the case in which 2s = 12. In a quadrupole field N decreases linearly with z (Fig. 4), i.e., the running losses dN/dz are constant, independent of the field over a wide range of values. Increasing the field without decreasing the running losses dN/dz nevertheless increases the quantity of plasma N passing through a given cross section of the tube. Thus it follows that increasing the magnetic field above a certain limit does not improve the self-channeling of the plasma (i.e., does not cut down running losses), but only decreases the quantity of plasma lost in the immediate vicinity of the gun. The fact that the curves of N = N(I) exhibit saturation shows that there are no plasma losses close to the gun.

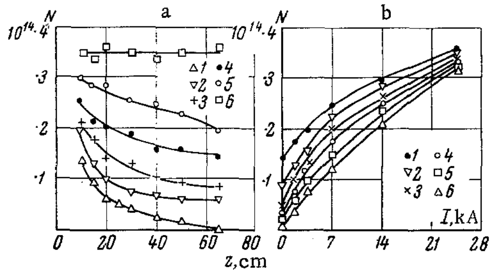


Fig. 6. (a) Change in the total number of plasma particles (2R = 9.8 cm) as the distance from the gun increases for various values of the magnetic field of a twelve-pole field; (a) values of I: 1) 0, 2) 1.4, 3) 2.8, 4) 7.0, 5) 14.0, 6) 28.0 kA. (b) Change in the total number of plasma particles passing through a cross section of the tube with an increase in the magnetic field of a twelve-pole field; vlaues of z: 1) 11, 2) 15, 3) 20, 4) 40, 5) 50, 6) 65 cm.

Similar results were obtained (Fig. 5) for a quadrupole with a somewhat different field structure (2R = 15 cm). The small discrepancy in the value of the constant dN/dz cannot be unconditionally ascribed to the change in field structure since the guns were not absolutely identical in these two cases: the mica lining of the gun had a different thickness in the case 2R = 15. This meant a small change in the parameters of the produced clusters, i.e., in the number of particles in a cluster (which is not of great significance), and possibly in the temperature.

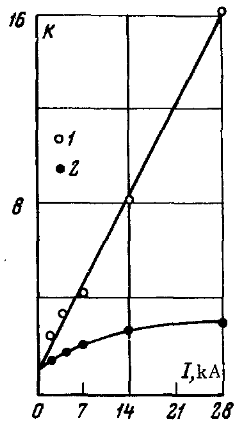


Fig. 7. Change in the inhomogeneity coefficient as the magnetic field increases for (1) 2s = 4 and (2) 2s = 12, z = 65 cm.

The motion of the plasma in a twelve-pole field is of quite a different character (Fig. 6). Here the running losses decrease both with an increase in field and also with z, and the function N = N(I) does not exhibit saturation. (Note that saturation must naturally ensue as the current is further increased since the amount of plasma produced by the gun is finite.) All other things being equal the

*Similar mechanisms may be treated in the case in question since the mean free path length $\lambda \gg 2R_0$. Actually setting the characteristic values for the present case $n = 10^{12}$ $p/cm^3$, T = 12 eV, into the formula $\lambda = 6 \cdot 10^{13} T^2 / n L_k$ and giving the Coulomb logarithm the value $L_k = 15$, we obtain $\lambda = 710$ cm.

Characteristic parameters of two-dimensional multipole fields for a current $I = 10^4$ (a), r(cm), H(0e), $\partial H/\partial r$(0e/cm), 2s/H (arbitrary units)

| s, R | $\theta = \theta_2$ | | | $\theta = \theta_1$ | | | |
|---|---|---|---|---|---|---|---|
| | $H_1$ | $H'_0$ | $H_2$ | $Q$ | $H_\theta\|_{r=R_0}$ | $H_\theta$ | $H_\theta\|_{r=0.5R_0}$ |
| $2s = 12,\ 2R = 9.8$ | 1420 | 1650 | 45 | 1 | 1570 | 2300 | 45 |
| $2s = 8,\ 2R = 9.8$ | 1390 | 700 | 196 | 0.68 | 1880 | 2150 | 196 |
| $2s = 6,\ 2R = 9.8$ | 1240 | 282 | 372 | 0.57 | 1980 | 1940 | 373 |
| $2s = 4,\ 2R = 9.8$ | 925 | −27.6 | 623 | 0.51 | 2080 | 1850 | 635 |
| $2s = 4,\ 2R = 15$ | 515 | 99 | 270 | 0.92 | 590 | 177 | 270 |

plasma losses in a twelve-pole field are less than in a quadrupole, and for a field with $I = 2.8 \cdot 10^4$ A the cluster is transported practically without loss from z = 11 cm to z = 65 cm. Thus it follows that the basic plasma losses are not associated with nonconservation of the adiabatic invariant, since an increase in the degree of multipolarity increases the region of the field where the adiabatic invariant is not conserved.

At this stage it is difficult to say whether the observed phenomena can be explained in the framework of some simple "slit" model, according to which plasma is lost at the walls of the tube, escaping through a "slit" in the magnetic field. We note, however, that if the "slit" width is assumed to be proportional to the Larmor radius (i. e., inversely proportional to the field), then the "total slit width" (product of the width of a single slit by the number of slits) is greater in the case 2s = 12 than in the case 2s = 4 (see table).

It is convenient to introduce the transverse inhomogeneity coefficient $k = N_1S/N$ to obtain a quantitative characteristic describing the uniformity with which the transverse section of the tube is filled with plasma. Here S is the cross sectional area of the tube. Clearly k indicates by how much the value of the plasma stream close to the axis exceeds the average value. It is clear from Fig. 7 that for large I and z the parameter k is an order larger in a quadrupole than in a twelve-pole field. Since the plasma losses from the axial regions are mush smaller than the general plasma losses (i. e., the plasma is lost basically from peripheral regions), it is clear that k increases as z increases.

It is convenient to describe the longitudinal spreading of a plasma cluster by means of the distribution function of longitudinal particle velocities $f(v)$ in the cluster being transported. Clearly the over-all number of particles passing through a given cross section of the tube for a current I is

$$N = \int f(v)\, dv\,.$$

It can be shown that the distribution function $f(v)$ may be obtained from the probe current as an experimental function of time $i = i(t)$ by means of the simple transformation $f(\nu) = iz/v^2$. (Two points must be noted here. First, the readings of the whole probe are used, i. e., $f(v)$ is a function averaged over the cross section.

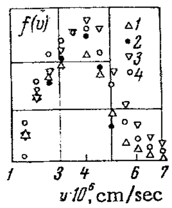


Fig. 8. Form of the velocity distribution function for particles in the magnetic field of quadrupole (1 and 2) and of a twelve-pole field (3 and 4) at two distances from the gun, z = 15 cm (1 and 3), z = 65 cm (2 and 4).

Second, strictly speaking, the function introduced as described above is a distribution function of average velocities, since the velocity is determined from the relation v = z/t, where t is the time of flight.)

When the experimental results are processed it turns out that the distribution function depends only feebly on the degree of multipolarity and the magnetic field strength. Figure 8 shows the distribution functions $f(v)$ normalized to unity for a velocity of $v = 3.5 \cdot 10^6$ cm/sec, at various distances from the gun.

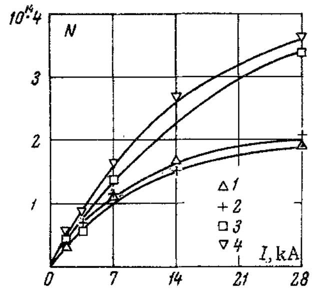


Fig. 9. Variation of the total number of plasma particles passing through a cross section of the tube (2R = 9.8 cm) at a distance of z = 65 cm from the gun for various degrees of multipolarity 2s: 1) 2s = 4, 2) 2s = 6, 3) 2s = 8, 4) 2s = 12.

It is clear from Fig. 8 that the distribution function changes little as the cluster moves, i. e., both fast and slow particles are lost in equal amounts (nevertheless, slightly more of the slow particles are lost). The fact that the distribution function $f(v)$ remains virtually unchanged as the cluster moves agrees with the qualitative intuitive assertion that the cluster moves as a whole with a constant mean velocity. The functions $N = N(z, I)$ of magnetic multipoles with 2s = 6 and 8 were also studied. It is evident from Fig. 9 that the results in such fields are intermediate between those of the cases 2s = 4 and 2s = 12.

Thus the results given above illustrate the possibility of using two-dimensional multipole magnetic fields for plasma transport.

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