Transport of plasma blobs magnetized at the entrance gradient in a profiled magnetic field

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The operation of a pulsed accelerator generating plasma blobs magnetized at the entrance gradient of a longitudinal magnetic field is investigated. It is found that at the field entrance the plasma conductivity is much less than the "Coulomb" conductivity. This leads to heating and increase of the specific energy content of the plasma and also to a decrease of the electron heat conductivity along the plasma flow. The feasibility of additional heating of the plasma on entrance into sharp contractions in the transport system is demonstrated. Information is obtained on processes involving the emission of a blob into a region free of magnetic fields.

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INTRODUCTION

In recent years, pulsed plasma accelerators yielded streams (blobs) of plasma with total energy content up to 100 kJ and with translational deuteron energy 5–6 keV.[1,2,3] The power of such streams reaches tens of GW, and the equivalent ion current is 5–10 MA. Different applications of accelerators of this type are possible. One of them is to fill magnetic mirrors used to solve problems of controlled thermonuclear fusion. From the parameters cited above of the actually obtainable plasma streams it can be seen that even now it is possible to produce with the aid of plasma accelerators systems in which at least the energy content and the ion temperature of the plasma will be at the levels attained in the modern installations such as T-10 and PLT.

The need for coupling a plasma accelerator with a magnetic mirror is dictated by the need for producing a system for transporting the plasma stream. The transport system must not only deliver the plasma to the mirror with a minimum loss, but also normalize the stream properties during the flight. In this paper we describe the result of investigations of one version of a plasma duct. When the experiment was planned it was proposed to obtain information on processes taking place in various parts of the plasma duct, with an aim at formulating problems for further development of its individual elements.

DESCRIPTION OF EXPERIMENT

The experimental setup is shown in Fig. 1. A plasma jet was produced by a pulsed coaxial accelerator 1, whose construction is described in detail in Refs. 1 and 2. The operating regime of the accelerator was determined by the choice of the initial voltage V_0 on the capacitor bank, from 12 to 25 kV, and by the delay time τ between the instant of entrance the working gas (deuterium) into the interelectrode gap and application of the voltage on the electrodes.

The plasma stream was introduced into the plasma duct 3. The plasma duct contained three solenoids of length 1.6 m each and a sectionalized vacuum chamber (liner) made of stainless-steel sheet 2 mm thick. The diameter and the total length of the first two sections of the liner were respectively 0.3 and 3.2 m. The third section had a conical transition piece (30 cm long) to a diameter 14 cm. The total length of the vacuum chamber reached 6.5 m. The vacuum chamber was evacuated by TMN-200 turbomolecular pumps to pressures 10^{-5} Torr. To decrease the influence of the magnetic field on the processes inside the injector, a demagnetizing steel disk 2 of 2 cm thickness was placed between it and the edge of the solenoid.

The solenoids in sections I, II and III produced a quasi-constant (period $T_0 = 10$ msec) magnetic field B_0. The voltage on the accelerator electrodes was applied 2.5 msec after turning on the field B_0, and the motion of the plasma jet took place in a practically time-constant longitudinal field. Each solenoid was separately fed, so it was possible to profile the magnetic field intensity along the flight chamber. The value of B_0 was varied from 0.7 to 10.8 kG. No magnetic field B_0 was produced in the region of section IV of the plasma duct (length 1.6 m).

The behavior of the plasma was observed by an assembly of diagnostic devices. Electric signals were registered with oscilloscopes of type S-1-42 and OK-17 m. Application of single time markers (from a distance calibrator "27I") and a reference pulse to all the oscilloscope beams made possible reduction to a single time scale and comparison of all the experimentally obtained oscillograms and interferograms (the latter were synchronized with a special spark generator).

Figure 1 shows schematically the arrangement of the 14 wall magnetic probes 4 and the system of the miniature magnetic probes 5. The object beam of the Mach-Zehnder interferometer passed through the viewing ports placed between sections of the plasma duct. The discharge currents were measured with Rogowski loops.

From the signals of the magnetic probes at the walls, which were spaced 8 cm apart along the system, we measured the velocity of the plasma blob and the magnetic field B_e in the gap between the liner and the plasma. In section IV, the four wall probes were located in each of two cross sections.

The system of magnetic probes 5 was arranged in a direction opposite to the plasma stream on a special holder and made it possible to determine the magnetic field intensity B_i inside the frontal part of the stream. The coils of the magnetic probes and the coaxial high-frequency cables leading from

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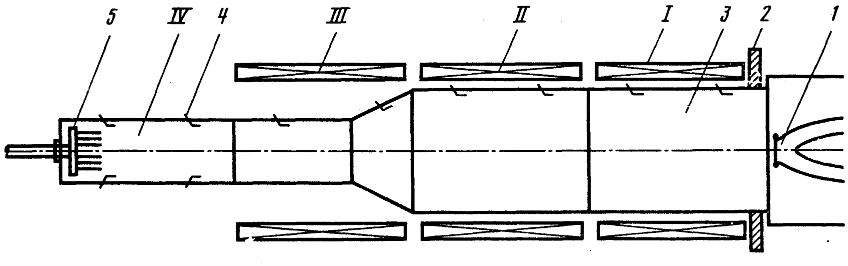

FIG. 1. Experimental setup: 1) injector; 2) demagnetizing disk; 3) vacuum chamber; 4) magnetic probes at the wall; 5) system of magnetic probes; I,II,III) solenoids of magnetic field B_0; IV) part of the vacuum chamber outside the magnetic field.

them were protected against contact with the plasma by thin (outside diameter 3 mm) glass tubes. All the magnetic probes operated in the regime of signal integration with the aid of RC networks.

A Mach-Zehnder interferometer (mirror diameter 250 mm) with a laser illuminator that generated light pulses of duration 200 μsec, and a high-speed photorecorder operating in the photographic scanning mode, were used to register the time variation of the radial distribution of the plasma-jet density.

MEASUREMENT RESULTS

The investigations of the interaction of the plasma streams with the magnetic field were carried out at $\tau = \text{const} = 360\ \mu$sec and at the following values of the initial voltage V_0:

1. $V_0 = 12$ kV, initial bank energy $W_0 = 43$ kJ;
2. $V_0 = 15$ kV, $W_0 = 67$ kJ;
3. $V_0 = 20$ kV, $W_0 = 120$ kJ;
4. $V_0 = 25$ kV, $W_0 = 190$ kJ.

Figure 2 shows a typical oscillogram of the signal of one of the wall probes. The plasma velocity was determined from the time shift of the fronts of such signals at a known distance between the probes. In the regime with $V_0 = 12$ kV, the velocity reached $2\cdot10^7$ cm/sec (ion energy $E_i = 400$ eV). With increasing V_0, the plasma-blob velocity increased and at $V_0 = 25$ kV it reached $7\cdot10^7$ cm/sec ($E_i = 5\cdot10^3$ eV).

The duration Δt of the probe signal increased as the blob moved along the plasma duct. This effect is a consequence of the longitudinal spreading of the plasma and is determined in all probability by the thermal expansion of the blob transported in a magnetic field. The probe-signal amplitude characterizes the degree of enhancement of the magnetic field in the gap between the plasma and the liner.

It must be noted that in this experiment the plasma enters into a longitudinal magnetic field without an experimentally observable loss of velocity, even if the energy density of the magnetic field exceeds the kinetic-energy density of the plasma blob. Thus, for example, for the operating regime in which $V_0 = 12$ kV, $B_0 = 7.2$ kG, $v = 2\cdot10^7$ cm/sec, and $n = 10^{15}$ cm^{-3} the density $P_{B_0} = B_0^2/8\pi = 12\cdot10^{17}$ eV/cm^3 and $P_{\text{pl}} = Mnv^2/2 = 4\cdot10^{17}$ eV/cm^{-3}, i.e., $P_{B_0} = 3p_{\text{pl}}$. Figure 3 shows plots of the maximum magnetic-field enhancement $\Delta B_e = B_e - B_0$ vs. B_0 in the first solenoid. What is typical is the constancy of ΔB_e in the investigated range of values of B_0 ($\Delta B_e = 700$, 1200, and 1400 G at $V_0 = 50$, 20, and 25 kV respectively). With further motion of the blobs along the plasma duct, the absolute values of ΔB_e decrease, but the relation $\Delta B_e = f(B_0) = \text{const}$ remains the same in each section of the plasma duct, i.e., at any chosen value of the field intensity the field enhancement does not depend on B_0, and is only a decreasing function of the distance z from the exit section of the accelerator to the measurement point.

Figure 4 shows plots of the magnetic field ΔB_i ($\Delta B_i = B_0 - B_i$) crowded out by the plasma in the first solenoid vs the magnetic-field intensity B_0 in vacuum. It can be seen that all the qualitative regularities for $\Delta B_i = f(B_0, z)$ remain the same as for ΔB_e. The absolute values are 500, 850, and 1000 G at $V_0 = 15$, 20, and 25 kV, respectively.

The "shock cone" in the third section of the plasma duct (Fig. 1) was intended to increase the density n and the temperature T of the plasma stream by exciting shock waves in it. The value nT of the plasma on passing through the cone was registered by determining the change of the amplitudes of the signals from diamagnetic probes. The observed $\Delta B_e(B_0)$ and $\Delta B_i(B_0)$ dependences in the zone behind the cone are similar in form to those shown in Figs. 3 and 4, and differ from them only quantitatively.

No magnetic field was produced in the last section of

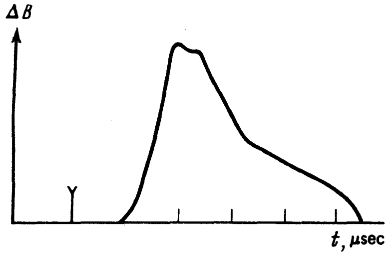

FIG. 2. Typical oscillogram of the signal of one of the magnetic wall probes.

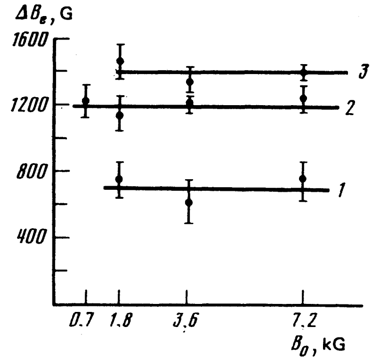

FIG. 3. Dependence of ΔB_e on B_0 in the first section of the plasma duct at: 1) $V_0 = 15$; 2) $V_0 = 20$; 3) $V_0 = 25$ kV.

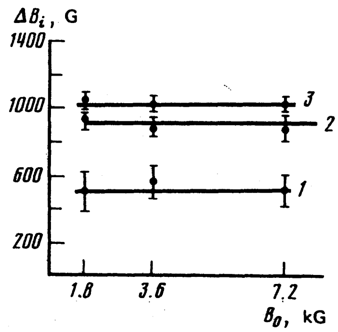

FIG. 4. Dependence of the magnetic field B_i crowded out by the plasma in the first section of the plasma duct on B_0 at: 1) $V_0 = 15$; 2) $V_0 = 20$; 3) $V_0 = 25$ kV.

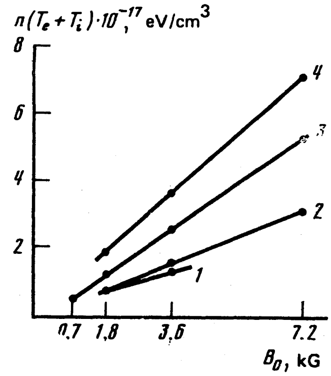

FIG. 5. Dependence of $n(T_e + T_i)$ on B_0 in the first section of the plasma duct: 1) $V_0 = 12$; 2) $V_0 = 15$; 3) $V_0 = 20$; 4) $V_0 = 25$ kV.

the plasma duct. This section was intended for the investigation of the regularities of the emergence of the magnetized stream (the magnetic field B_i reached 9 kG prior to the entry into section IV) from the magnetic field B_0. It was established with the aid of magnetic probes that the direction of the magnetic field B_i carried away by the plasma coincides with the direction of the field B_0. The field intensity increases towards the outer layers of the plasma blob, and at its boundary the sign of the field is reversed. The absolute values of B_i in all the regimes up to $V_0 = 20$ kV did not exceed 300 G. For $V_0 = 25$ kV, a linear dependence of B_i on B_0 is observed. In this regime we registered the maximum value of the field B_i frozen in the plasma. It reaches 1.5 kG at $B_0 = 10^8$ kG. The measurements of the plasma density with the aid of a Mach-Zehnder interferometer made it possible only to estimate its value. It turned out to be $\sim 10^{15}$ cm^{-3}.

DISCUSSION OF MEASUREMENT RESULTS

It is best to carry out the discussion separately for each of the characteristic sections of the plasma ducts, and formulate the general deductions in the conclusion.

1. Entry of the flux into the plasma duct and transport in a longitudinal field (sections I and II)

The equation for the conservation of the magnetic-field flux in the liner is of the form

$$B_0S_0=B_e(S_0-S_i)+B_iS_i, \tag{1}$$

where $S_0 = \pi R^2$ is the area of the liner cross section; $S_i = \pi r^2$ is the cross-section area of the plasma blob. Hence

$$S_i=S_0\Delta B_e/(\Delta B_e+\Delta B_i). \tag{2}$$

For the relations $\Delta B_e(B_0)$ and $\Delta B_i(B_0)$ established in the experiment we have $S_i =$ const or, in other words, the radius of the plasma stream does not depend on B_0 and is equal for the first plasma-duct section to 8, 10, and 10 cm respectively at $V_0 = 15$, 20, and 25 kV. In the second section, the radius of the bunch decreases by 15–50%. This phenomenon is attributed to the longitudinal spreading of the plasma, so that it is impossible to establish the rate of the transverse diffusion with the aid of the employed procedures. We recall that the liner diameter is 30 cm.

Radial spreading of the plasma is prevented by the pressure of the magnetic field. The pressure-balance equation $P + B^2/8\pi =$ const can be reduced to the form

$$n(T_e+T_i)=\frac{10^{11}}{4}[2B_0(\Delta B_e+\Delta B_i)+(\Delta B_e^2-\Delta B_i^2)]. \tag{3}$$

It is easy to show that for the experimental dependences of ΔB_e and ΔB_i on B_0 the gaskinetic pressure of the plasma depends linearly on B_0. The corresponding plots are shown in Fig. 5. It can be seen that at $V_0 = 12$ kV the slope of the line is smallest. With increasing V_0, the derivative $\partial[n(T_e + T_i)]/\partial B_0$ increases. It reaches the maximum values at $V_0 = 25$ kV. Thus, for $B_0 = 1.8$ kG we have $n(T_e + T_i) = 1.8\cdot10^{17}$ eV/cm^3, and at $B_0 = 7.2$ kG the plasma pressure increases to $7\cdot10^{17}$ eV/cm^3. It should be noted that the density n of the particles in the streams lies in the range 10^{15}–$3\cdot10^{15}$ cm^{-3} and is independent, within the limits of errors, of the magnetic field. From a comparison of the presented data it can be seen that the total plasma temperature in the stream reaches several hundred eV. Its temperature in the accelerator gaps lies in the range 1–10 eV (Refs. 2,4,5). It follows therefore that the stream is intensively heated at the entrance into the transport system.

Figure 6 shows the dependence of $\beta_e = 8\pi n(T_e + T_i)/B_e^2$ on B_0 as calculated from the experimental data. It can be seen that β_e increases with increasing V_0 and with decreasing

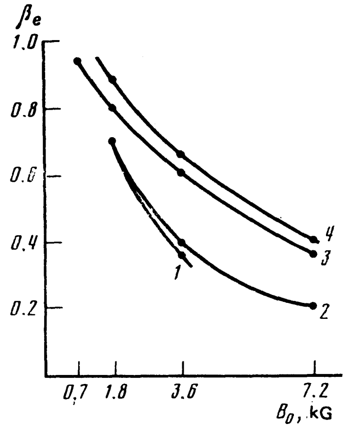

FIG. 6. Dependence of β_e on the value of B_0 in the first section of the plasma duct at: 1) $V_0 = 12$ kV; 2) $V_0 = 15$ kV; 3) $V_0 = 20$ kV; 4) $V_0 = 25$ kV.

B_0. The entire aggregate of the data obtained in the experiments (independence of the stream radius of B_0, plasma heating, magnetization) can be attributed to rapid diffusion of the magnetic field into the plasma at the entry into the transport system. The times of classical diffusion for $T_e = 3$–10 eV under the experimental condition amounts to several hundred microseconds. The times of flight of the blob from the end face of the accelerator to the chosen observation regions amounts to several (0.5–10) μsec. It must therefore be assumed that there exist anomalous mechanisms of "magnetization" of the stream. The latter are usually due to the development of small-scale instabilities. One of them can be the buildup of ion-sound plasma oscillations. The necessary conditions for the onset of oscillations are the relations[6,7]:

$$T_e > 3T_i, \quad v_S \ll v_{dr} < v_{Te}, \tag{4}$$

where v_S is the velocity of the ion sound and v_{Te} is the thermal velocity of the electrons.

The electron drift velocity v_{dr} is connected with the current density by the relation $j = nev_{dr}$. The current density in the plasma entering in the magnetic field is given by the relation

$$j = -\frac{c}{4\pi}\frac{\partial B_z}{\partial r} = -\frac{c}{4\pi}\frac{\Delta B}{\Delta r}. \tag{5}$$

Substituting in this expression the measured value of the field jump on the boundary of the plasma stream and its radius (at 30 cm from the end surface of the accelerator the current flows over the entire cross section of the blob) for one of the regimes ($V_0 = 25$ kV), we obtain $j = 5\cdot 10^{11}$ absolute units. We note that the current density j for each value of V_0 does not depend on B_0. For $n = 10^{15}$ cm^{-3} we have $v_{dr} = 10^6$ cm/sec. At the entrance of the plasma blob into the magnetic field, the width of the plasma layer in which the magnetic-field jump takes place is determined by the classic conductivity and is smaller by 1.5 orders of magnitude than the radius of the stream in the plasma duct. It is precisely in the skin layer that the buildup of the ion-sound oscillations begin. The conditions for the "divergence" of the electron and ion temperatures on account of the Joule heating of the electron also appear in this layer. Noise can be produced in the plasma also by Rayleigh-Taylor instability. The conditions for its appearance occur when the stream slows down or when its trajectory at the entrance to the system becomes bent.

One of the features of the noise level in the plasma is its conductivity σ. The measured times of the disintegration of the skin layer and of the total magnetization of the plasma blob as it enters the plasma duct (in our experiment they are equal to the times of the travel of the plasma through the region of the entrance gradient of the magnetic field, i.e., they amount to $t \sim 0.5$ μsec) make it possible to estimate the quantity

$$\sigma = c^2 t / 4\pi r^2, \tag{6}$$

which turns out to be at the level of 10^{11}–$5\cdot 10^{11}$ absolute units, i.e., smaller by approximately two orders of magnitude than the conductivity calculated from the equation

$$\sigma \approx 10^{13} T^{3/2} \tag{7}$$

for the characteristic temperatures of streams in plasma accelerators. Such a low conductivity confirms the existence of turbulence of the stream in the zone of the "entrance" gradient of the magnetic field of the plasma duct. When the blob moves through the plasma duct, the oscillations, in all probability, attenuate. In the opposite case, the plasma of the stream should go off to the liner wall in the course of its motion.

The low conductivity of the plasma contributes to rapid diffusion of the magnetic field and to Joule heating of the electrons as the stream enters the plasma duct. The heated electrons are dragged by the stream along the plasma duct. Their temperature, as noted above, reaches several hundred eV. The mean free path of such an electron is approximately one meter and is commensurable with length L of the blob. In this case the plasma cooling time should be determined by the heat loss due to energy transported by the electrons to the end of the accelerator at thermal velocities (quasineutrality is ensured by the additional inflow of cold electrons) and is equal to $L/v_{Te} \approx 100$ nsec. Experiment, however, indicates that the plasma has large nT in the course of the entire travel time (~ 10 μsec). In all probability, the plasma noise at the entrance into the magnetic field limits strongly the rate of departure of the electrons from the system. In fact, the effect of the frequency ν_{eff} of the electron collisions in the zone of the entrance gradient of B_0 is

$$\nu_{eff} = ne^2/\sigma m_e. \tag{8}$$

For $\sigma = 10^{11}$ absolute units we have $\nu_{eff} = 5\cdot 10^{12}$ sec^{-1} and the electron diffusion coefficient is $D = v_{Te}^2/3\nu_{eff} \approx 10^5$ cm^2/sec in the temperature interval from 10^2 to 10^3 eV. Therefore during the time of flight of the blob the temperature front moves over a distance $\Delta = (Dt)^{1/2} = 1$–2 cm, and the entrance-gradient zone is a sort of "thermal barrier" for the heat flow from a plasma blob moving in the magnetic field of the plasma duct.

2. Interaction of flux with the shock cone (section III of the plasma duct)

The task of entering the plasma stream into the magnetic trap calls for rapid heating of the blob along the path.[8] This can be done in two ways: by increasing the magnetic field within times shorter than the time required for the blob to travel over the heating region, or by producing in the plasma duct abrupt transitions protected by the magnetic field (shock cones) in the cross section of the plasma duct. Simple estimates show that the former method imposes rather stringent requirements on the electrotechnical devices (the field growth time should be less than 1 μsec). We deemed it advisable to carry out preliminary investigations aimed at observing the heating effect in the interaction of a plasma stream with a shock cone. The experiment was performed in two variants. In the first variant the vacuum magnetic field B_{sh} in section III coincided with the vacuum field B_0 of sections I and II, while in the second variant $B_{sh} > B_0$. In both cases we estimated the quantity

$$k = [n(T_e + T_i)]_{III}/[n(T_e + T_i)]_{II},$$

i.e., the degree of heating of the plasma on passage through the constriction of the plasma duct. For the case $B_0 = B_{sh}$

TABLE I. Results of measurements of the parameter k

U_0, kV	$B_0 = B_{sh}$, kG		
	1.8	3.6	7.2
15	1.9	2.6	2.9
20	1.1	1.4	1.5

the measured values of k are listed in Table I. It can be seen from the table that in all the regimes one observes a noticeable increase in the specific energy content of the plasma. The decrease of k with increasing V_0, i.e., at a corresponding increase of the stream velocity head, can be explained as being due to partial diversion of the plasma to the cone wall.

A comparison of the internal magnetic fields B_i in sections II and III has shown that $B_{i,\mathrm{III}}$ is always 1.5–2 times smaller than $B_{i,\mathrm{II}}$. This fact is evidence of a shock-wave mechanism of plasma heating.

In the variant with $B_{sh} > B_0$, we observed also a substantial increase of the specific energy content. Thus, at $V_0 = 15$ kV, $B_0 = 1.8$ kG and $B_{sh} = 10.8$ kJ we have $k = 18$. The magnetic probes show that in the investigated regimes ($1.8 \leqslant B_0 \leqslant 3.6$ kG, $3.6 \leqslant B_{sh} \leqslant 10.8$ kG) the field $B_{i,\mathrm{III}} = (1.5\text{–}2.5)\, B_{i,\mathrm{II}}$. It must therefore be assumed that the growth of the nT of the plasma is determined by the joint action of the shock-wave and "diffusion" heating mechanisms.

3. Exit of the stream from the magnetic field (section IV of the plasma duct)

An investigation of the characteristics of the flow at the exit from the plasma duct is a natural stage in the solution of the transport problem. For a plasma temperature $T = 10$–100 eV and a stream velocity $5\cdot 10^7$ cm/sec, the transverse magnetic Reynolds number lies in the interval $10^3 < \mathrm{Rm} < 5\cdot 10^4$. Therefore at the exit from the plasma duct one should expect a strong interaction between the stream and the magnetic field, capture of the field by the plasma, and formation of blobs with their own currents and fields. We note that methods of producing such structures are of independent interest. The open magnetic mirror[2] XIIB is filled with plasma with the aid of one of these structures.[9]

The fields observed by us experimentally in the bunch at the level of several hundred gausses. Their intensity does not exceed 10% of B_i in section III of the plasma duct. In all probability, at the exit from the system the field is intensively "frozen out" of the plasma. The nature of this process is analogous to the mechanism of anomalous magnetization of the plasma at the entrance. High-temperature plasma streams with small self-fields are of interest from the point of view of their injection into magnetic mirrors with $\beta = 1$, and also in a large number of applications.

CONCLUSION

In the investigated operating regime of an accelerator-plus-plasma-duct system, the qualitative picture of transporting the stream in a longitudinal magnetic field appears to be the following. In the region of the entrance gradient of the magnetic field of the plasma duct, the plasma stream becomes rapidly magnetized. The time of diffusion of the field into the plasma is much shorter than the diffusion times calculated from the Coulomb conductivity, and is determined by the rate of development of instabilities in this zone. The lifetime of the plasma with high noise level is determined not only by the time of flight of the frontal part of the stream. It exists in all probability during the entire time that plasma is fed from the accelerator.

The diffusion of the field into the plasma is accompanied by heating of the latter. Transport of such a stream in the homogeneous field of the plasma duct takes place without noticeable energy loss. This demonstrates that in such a field the plasma oscillations are attenuated and that the rate of diffusion of the plasma to the liner wall decreases and is determined by a conductivity close to the Coulomb value. In the direction of the magnetic-field force lines, the plasma temperature is constant over the entire length of the stream. Plasma cooling is hindered by a "thermal barrier" that exists in the zone of the entrance gradient of the magnetic field.

The passage of the blob through the abrupt constrictions of the plasma duct is accompanied by a noticeable increase of the specific energy content of the plasma. The heating mechanism depends on the initial conditions of the entrance into the transition zone. They can be either shock waves or dissipation of the directed energy of the stream by the plasma turbulence.

When the blob exits into a region free of magnetic fields, a plasma formation with magnetic self-fields and currents is produced. The structure of these fields is similar to that produced in θ pinches with inverse field and when compact toroidal configurations with closed force lines are formed.[10] The order of magnitude of the intensity of the magnetic self-field of the blob is determined by the "demagnetization" of the plasma at the exit from the solenoid, and reaches 10% of the intensity of the internal field of the plasma in the transport system.

In conclusion it should be noted that the set of experiments described above is preliminary. There are all grounds for assuming that by choosing the proper structures of the magnetic fields in the plasma duct and the proper operating regimes of the plasma accelerators the effects observed will become enhanced both with respect to development of plasma streams with $\beta < 1$ and with respect to production of plasma formations with $\beta = 1$.

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