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The scientific session of the Division of General Physics and Astronomy of the USSR Academy of Sciences was held on 31 January 1990 at the USSR Academy of Sciences S. I. Vavilov Institute of Physics Problems. The following reports were presented:

1. A. S. Borovik-Romanov. Spin Superfluidity in ^{3}He-B.

2. A. I. Morozov. Development of the Principles of a Quasi-Steady-State Plasma Accelerator with an Intrinsic Magnetic Field with a Power of 10^9–10^{11} W.

A summary of one report is given below.

A. I. Morozov. Development of the Principles of a Quasi-Steady-State Plasma Accelerator with an Intrinsic Magnetic Field with a Power of 10^9–10^{11} W. This report discusses work being conducted in the USSR on the creation of powerful ($\sim 10^9$–10^{11} W) quasi-steady-state (~ 0.1–1.0 ms) plasma accelerators (QSPA) with magnetically insulated electrodes which provide a flux of hydrogen plasma in the keV range.

The creation of a QSPA is not only important for science, but is also of great interest from the point of view of widely varied applications: problems of controlled thermonuclear fusion, plasma technology in heavy machine building, large scale experiments in space, the generation of powerful electromagnetic radiation up to the x-ray range, etc. In principle,a QSPA is a system of two coaxially profiled electrodes with a large discharge current (~ 100–1000 kA) flowing between them (Fig. 1). Due to the intrinsic azimuthal magnetic field H and the quasi-radial current j_r, a z component of the Ampere force is generated

$$f_z = \frac{1}{c} j_r H_\theta, \qquad (1)$$

which accelerates the plasma entering the channel. Within the framework of an ideal one-fluid magnetic hydrodynamic model, the Bernoulli integral is maintained along the line of the plasma flow

$$\frac{v^2}{2} + i(\rho) + \frac{H^2}{4\pi\rho} = \frac{H_0^2}{4\pi\rho_0} \equiv c_{A0}^2; \qquad (2)$$

here $i(\rho) = \mathrm{d}p/\mathrm{d}\rho$ is enthalpy, and c_A is the Alfén speed, and the values of the parameters at the entry to the channel are recorded as zero, $v_0 \to 0$, $i(\rho_0) \to 0$. From (2) it follows that the maximum attainable speed of outflow of plasma in the QSPA is

$$v_{\max} = \sqrt{2} c_{A0}, \qquad (3)$$

that is, of the order of the Alfén speed at the entry to the channel, just as gas flows from an ordinary Laval nozzle with a speed of the order of the initial speed of sound c_{T_0}.

From the law of conservation of momentum, it follows that

$$(v_M)_{\mathrm{cm/s}} = \frac{1}{\dot m} \int \frac{H^2}{8\pi} \mathrm{d}s_z = \theta \cdot 10^{-2} \left(\frac{I_p^2}{\dot m}\right)_{\mathrm{A^2/g}}; \qquad (4)$$

here $\dot m$ is the consumption of matter per second, I_p is the discharge current, and θ is a geometric factor.Thus, for $I_p = 1$ MA, and $\dot m = 100$ g/s, one should expect $v_M \sim 10^8$ cm/s.

For this flow to be matched with the electrodes, one must consider the Hall effect, that is, the difference in the movement of the ions and the electrons. The qualitative properties which arise here may be understood in the model of the movement of "single" ions and electrons. The main property of the QSPA as an accelerator is that the electrons and ions are "magnetized" in the channel and, in the first approximation, drift with a velocity

$$v_z = \left(\mathbf{u}_E = c\frac{[\mathbf{EH}]}{H^2}\right)_z = c\frac{E}{H}. \qquad (5)$$

From (5) it is clear that to increase the velocity of the particles one must increase **E** or decrease **H**. This mode of acceleration is called a "drift" mode. Obviously, acceleration actually occurs due to the displacement of ions to the cathode ($\sim m_i/e$) and electrons to the anode ($\sim m_e/e$). Consequently, if the particles enter the channel only through the entry cross section, a region will be formed near the anode which is depleted in ions. A large jump in potential should be generated in this region. At the same time, ions move to the cathode. This conclusion is confirmed in an extreme way by experiments in an accelerator with solid electrodes.[1,2] To avoid this when there are equipotential electrodes, one must continuously supply ions into the channel from the anode and take them from the cathode. If one then considers that the electrons move virtually along equipotentials (that is, parallel to the electrodes), then we arrive at the necessity of ensuring ion current transfer[1,2] in the channel of the QSPA. To implement this, the electrodes should be changed into devices to convert the current carrier, "transformers." The anode transformer should contain plasma generators from

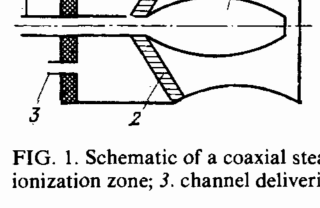

FIG. 1. Schematic of a coaxial steady-state accelerator. *1.* electrodes; *2.* ionization zone; *3.* channel delivering the working substance.

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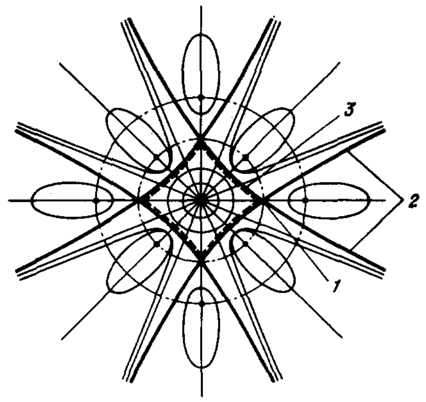

FIG. 2. Magnetic configuration of the anode transformer. *1.* "transport channel" line of zero magnetic field; *2.* "barbs; *3.* magnetic emitting surface.

which the ions are drawn, and the cathode transformer should contain a removal system. If the QSPA is being designed for large energy input, then the transformers, or more accurately, their solid-state elements, and primarily the cathode transformer, require magnetic shielding from the strong accelerated flow. Obviously,these requirements may be satisfied only using magnetic fields which contain self-intersecting separatrix surfaces. In this case by creating a field whose separatrix contains a closed quasi-cylindrical fragment of the encompassing channel, we can use it as a magnetic emitting surface. At the same time the other fragments of the separatrix which approach it from outside ("barbs") may be used to remove electrons to the "closing" electrodes). Figure 2 shows one of the possible magnetic configurations of the anode transformer. It is called a "*z*-configuration" since it is formed by current-carrying conductors extended along the channel. This configuration is reminiscent of the magnetic configuration of a tokamak with a poloidal diverter. These separatrices may be used to transport plasma from the "anode ionization chamber" to the entire surface of the magnetic emitting surface. The described design of the *z*-transformer is by no means the only design, but we will not dwell on others. The magnetic configurations of cathode transformers may be done analogously.

In addition to transformers which form the main accelerator stage, there is another first stage in the QSPA, the "input ionization block," in which ionization and preliminary acceleration of the working substance occurs. Between the first stage and the main stage is the "drift channel," in which the necessary "adjustment" of the parameters of the flow are made for entry into the main stage.

To create and study experimentally such a unique and complex plasmodynamic machine as the QSPA, a cooperation was created of several small groups working in various institutes in the country. Here one should primarily note the groups of K. V.Brushlinskiĭ (USSR Academy of Sciences M. V. Keldysh Institute of Applied Mathematics), V. I. Tereshin, and V. V. Chebotarev (Ukrainian SSR Academy of Sciences S. M. Kirov Kharkov Physicotechnical Institute), Yu. V. Skvortsov and V. G. Belan (FIAE Branch of the Institute of Atomic Energy), and V. M. Astashinskiĭ and L. Ya. Minko (Belorussian SSR Academy of Sciences B. I. Stepanov Institute of Physics). The I.V. Kurchatov Institute of Atomic Energy became the chief organization. This work has been supervised at this institute since 1973 by A. P. Aleksandrov and E. P. Velikhov.

In the seven years since the formation of the cooperation, a solid experimental base has been created which is equipped with capacitance and inductance accumulators up to the megajoule range, the required vacuum equipment, and control systems. A variety of designs of all the elements of the QSPA were developed, which, in the process of the experiments were optimized. Thus, the small anode ionization chambers (5 cm in diameter, 20cm in length) made it possible to obtain plasma flows of hydrogen with an equivalent ion current I_i^{equiv} up to 30 kA, and the input ionization block provided flows with I_i^{equiv} up to 1–2 MA with speeds of ~ 50 km/s. A "global numerical simulation of the QSPA" (the expression of A. N. Tikhonov) was carried out, including the creation of three-dimensional non-steady-state codes.

Considering the complexity of the "full-block" model of the QSPA, the first stage of comprehensive studies was done using simplified two-stage P-50 type models in which the transformers were core-type systems, and the source of ions for current transfer was an ionized gas in a vacuum chamber in the region beyond the anode. The number 50 in the name of the model indicates the diameter of the anode in centimeters. The P-50 studies made it possible to test the experimental equipment in the presence of many discharge and auxiliary high-current circuits, to choose the optimal diagnostics, and most importantly, ascertain the possibility of controlling the discharge in the accelerator.

Study of the **E** and **H** fields in the channel in various P-50 modifications showed that by choosing conditions at the entrance and in the neighborhood of the anode and by changing the parameters of the discharges in the input ionization block and in the main stage, one could obtain very different distributions of these parameters, including the "calculated" ones (Ukrainian SSR Academy of Sciences S. M. Kirov Kharkov Physicotechnical Institute, FIAE, Belorussian SSR Institute of Physics). The maximum output parameters of the plasma flow were obtained at the Ukrainian SSR Academy of Sciences S. M. Kirov Kharkov Phyiscotechnical Institute ($I_i^{\text{equiv}} \sim 1$–2 MA, $\varepsilon_i \sim 1$ keV, $\tau_{\text{work}} \approx 50$ μs). For more details see Reference 3.

At present (January 1990) the "full-block" K-50 models are being mastered, in which it will be easy to control the operation of the transformers. There is a basis for the hope that by the end of this year, better P-50 results will be obtained in these models, which will create the basis for a further increase in the output parameters.

[1]K. V. Brushlinskiĭ, A. I. Morozov, L. S. Solov'ev, [Russ. original Rev. Plasma Phys. **8**, 1 (1980), Consultants Bureau, N.Y. Voprosy teorii plasmy, Atomizdat M., **8**, 3 (1974)].
[2]A. K. Vinogradova, P. E. Kovrov, A. I. Morozov, A. P. Shubin, Physics and the Use of Plasma Accelerators (In Russian) Nauka i tekhnika, Minsk, 1974, p. 78.
[3]A. I. Morozov *et al.*, Fiz. plazmy **16** (2), 3 1990 [Sov. J. Plasma Phy. **16** (1990)].

Translated by C. Gallant