POWERFUL QUASISTATIONARY PLASMA ACCELERATOR.


Since several years an intensive program performed at the IPP (Institute of Plasma Physics National Scientific Center Kharkov Physics and Technology Institute) for investigation and development of high-power quasistationary plasma accelerator. The general principles of the quasistationary plasma acceleration proposed by A.I.Morozov [1]. They are as follows: 1 - transition to a two-stage scheme of acceleration (the first stage provides the working gas ionization and preliminary acceleration of plasma streams, thereby suppressing the detrimental effect of the ionization region instability on the parameters of the generated streams); 2 - the magnetic screening of the electrodes in the main accelerating channel (to prevent high energy particles bombardment of the electrodes); 3 - transition to the mode of operation, under which the electric discharge current in the main accelerating channel is carried by ions (to remove the problem of potential jumps in the vicinity of the electrodes). These principles realized in plasma accelerator QSPA Kh-50 [2] (two-stage quasistationary plasma accelerator with active anode and semiactive cathode).

The main attention in experiments paid to analysis of the integral electro-technical characteristics of these accelerators, local characteristics and the physical properties of plasma flow in the main accelerating channel, analysis of parameters of plasma streams, generated by QSPA Kh-50 accelerator, by variation of boundary conditions on electrodes. The efficiency and thrust of the main accelerating channel are present too.

1. Experimental device and diagnostics.

The experiments were carried out on the installation QSPA Kh-50 (full-scale two stage accelerator with active anode and semiactive cathode transformers). Accelerator consist of three main units: 1) an input ionization system (1st stage); 2) an anode transformer ($T_a$); 3) a cathode transformer ($T_c$) forming together with $T_a$ the main acceleration channel (2nd stage). The anode and cathode transformers are separated by a ring insulator. The block diagrams of the accelerators are shown in Fig 1. The first stages comprise the input ionization units and the drift channels. The input ionization unit of accelerator consists of five individual input ionization chambers (IIC). Each IIC is a relatively low-power coaxial plasma accelerator with nontransparent electrodes, the cylindrical anode being 8 cm in diameter. The separate plasma streams generated by every the IIC spread

Fig. 1 Experimental layout of the experimental device QSPA Kh-50;
1: anode transformer; 2: anode collector; 3: anode transformer pies; 4: cathode transformer rods; 5: anode ionization chamber; 6: drift channel; 7: input ionization chambers; 8: needle-type emitters

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azimuthally and radially in the drift channels. The spacing between the IIC outputs and the input to the second stage is about 80 cm.

The magnetic system of the QSPA Kh-50 anode transformer is a ten-pole three-row set of longitudinal rods arranged in pies. The electrical current flowing in the pie rods, as well as the discharge current flowing in the anode collector and in the cathode transformer components form the magnetic emitting surface (MES) with an average diameter of 50 cm, a length of 80 cm. The MES comprises ten zero magnetic field lines stretched along the Tc. Along these lines a plasma propagates. The plasma is generated by the anode ionization chambers (AIC). The AIC are wholly similar in design to the IIC, but are of a smaller size (the anode diameter is 5 cm). The ions going off the MES to the accelerating channel sustain the process of current transport.

The semiactive cathode transformer (Tc) consists of the cylindrical support component and the shaped rod-like working part, which has a 62 cm length, the largest diameter in the critical cross section being 36 cm. The rods are made hollow. Inside the rods there are the current-carrying conductors insulated over the whole length, which form the magnetic system of the Tc. The discharge current takes its path to the Tc rods via the needle-type cathodes fixed on the inner surface of the rods.

The working gas is supplied separately to each IIC and AIC by means of pulsed electrodynamic valves. The working gas is hydrogen.

The accelerators are installed in a vacuum chamber, 10 m long and 1.5 m in diameter. The chambers are pumped by number of turbopumps TMP-500 and titanium sorption pumps, providing an ultimate pressure of about 10^{-5} torr.

The power supply systems consist from capacitor banks with total energy 4 MJ. More details about the experimental setup can be found in [2,3].

The instrumentation for diagnostics of plasma flow in the accelerating channel and the parameters of the generated plasma streams includes a set of Rogowsky coils, frequency-compensated voltage dividers, electric and magnetic probes, local calorimeters, high-speed cameras. The plasma stream density was determined from the Stark broadening of the H_p and self-absorption H_a spectral lines and also by using the long-baseline (200 mm) interferometer. The velocity of different parts of the plasma stream was measured on the basis of time-dependent modulation of radiation using the slit scanning and registration by a high-speed camera, as well as by measuring the Doppler shift of spectral lines CII (λ=4267 Å) and self-absorption H_alpha. Electron temperature was evaluated by the ratio of spectral lines intensities, or by the analysis of contours of self-absorption spectral line H_alpha.

2. Experimental results.

The experiments were carried out at a voltage of the main-discharge capacitor bank up to 15 keV for QSPA Kh-50 (I_d < 800 kA), as well as for different mass rates of flow and different ways of switching on the magnetic systems of the anode and cathode transformers.

2.1. Integral characteristics of the QSPA.

On the basis of energy and pulse conservation laws one able to find two relations between five main plasma accelerator characteristics: I_d (discharge current), U_d (electrode voltage), I_m (working gas flow rate), v (plasma velocity) and η (main stage accelerator efficiency) [1]. In simplified form they are as follows: v ~ I_d^2 / I_m; U_d ~ η I_d^2 / I_m. The current-voltage characteristics (CVC) of the discharges were approximated by the power function U_d ~ I_d^α with the index α being within 1.5 < α < 2.9 for QSPA Kh-50. The highest values of index α were achieved in optimal conditions with improved anode gas supplying by switching on AICs with optimum gas filling. In this case experimental CVC was in good agreement with calculated one. Examples of CVCs and velocity dependence on discharge current, measured practically simultaneously, are shown in Fig.2. Here are drawn as well the functions η (I_d) and η (I_d), calculated on the basis of first two measured dependencies.
The current-voltage characteristics (CVC) of the discharges were approximated by the power function $U_d - I_d^\alpha$ with the index $\alpha$ being within $1.5 < \alpha < 2.9$ for QSPA Kh-50. The highest values of index $\alpha$ were achieved in optimal conditions with improved anode gas supplying by switching on AICs with optimum gas filling. In this case experimental CVC was in good agreement with calculated one. Examples of CVCs and velocity dependence on discharge currents, measured practically simultaneously, are shown in Fig.2. Here are drawn as well the functions $Im (I_d)$ and $\eta (I_d)$, calculated on the basis of first two measured dependencies.

2.2. Current topograms in the main accelerating channel.

In the Fig.3 are shown the current topograms obtained in the full-scale accelerator under different conditions of the magnetic screening of the transformers. One can see in Fig. 3a - 3b that, when there is no magnetic screening of transformers (a), or cathode rode current has opposite sign (b), or cathode current is too high (c), there is no regular plasma flow in main accelerating channel - the current vortices are produced at the input to the accelerating channel and current lines are sliding along the electrodes. But when the magnetic screening of the transformer elements is optimal (d, e, f), therefore the anode emitting surface is produced, the current in the accelerating channel flows practically radially over $>250 \mu s$ for the total discharge duration of about $300 \mu s$.

![Current topograms in the main accelerating channel of the QSPA Kh-50.](image)

- Fig.3. Current topograms in the main accelerating channel of the QSPA Kh-50.
- a - $U_c = 6 \, kV$, $I_{te} = I_d = 0$; b - $U_c = 6 \, kV$, $I_{te} = -50 \, kA$, $I_d = 0$; c - $U_c = 12 \, kV$, $I_{te} = 220 \, kA$, $I_d = 30 \, kA$; d, e, f - $U_c = 12 \, kV$, $I_{te} = 75 \, kA$, $I_a = 30 \, kA$; g-f $\Delta V_{nc} = 175 \, cm^3$, $\Delta V_{arc} = 75 \, cm^3$, $I_{d_{nc}} = 70 \, kA$, $I_{d_{arc}} = 30 \, kA$. 

Two conclusions one possible to produce, analyzing this figure. The accelerator efficiency is growing monotonously with the discharge current. In the case of optimal anode gas filling only the gas flow rate is not a function of discharge current. That is the reason for the CVC behavior in agreement with theoretical predictions.

*Fig.2. Integral characteristics of QSPA.*

$I_d$ - current of the discharge; $U_d$ - electrode voltage; $I_{ma}$ - gas filling (in current units); $v$ - plasma velocity.
3. Analysis of plasma flow main property in the accelerating channel.

On the bases of the experimentally measured topograms of currents (see fig. 3.d,e,f) and potentials ($H$ and $\phi$ topograms) we can calculate of such parameters as electron and ion velocities $v_e(r)$, $v_i(r)$ and density topograms $n$.

The calculation allows to obtain a number of fundamental properties of plasma current in the profile channels such as a current transport mechanism, a flux velocity transition over the local velocity of a signal as well as to receive the information on flow isomagnicity and isobernoully.

3.1 Flow calculation model.

The calculation was carried out with the following assumptions:

1) The plasma flow considered to be stationer; $\partial ... / \partial t = 0$;
2) the magnetic field supposed to be axial-symmetrical only with the azimuthal component $H_\theta$ ($H_\phi = 0$);
3) the electron inertia was neglected;
4) there were conditions of a whole absence of impurities and viscosity.

We apply of two-fluid magnetic hydrodynamics using the flux function $[1]$

$$
\ln v_e^e = \frac{\partial \psi_e^e}{\partial r}, \quad \ln v_i^e = - \frac{\partial \psi_e^i}{\partial z}
$$

(1)

Then, considering the above-mentioned assumptions for the cold electron component, it is possible to write down two laws of conservation

$$
-e \psi = U_e(\psi) \quad (2)
$$

$$
\frac{H}{n r} = - \frac{1}{c} \frac{\partial \phi}{\partial \psi} \quad (3)
$$

and to preserve the Maxwell equation in the form:

$$
\frac{4 \pi e}{c} (\psi_i - \psi_e) \quad (4)
$$

It follows from eq. (2), that electrons move along the lines of equal potential. Hence, the form of the lines $\psi_e = \text{const}$, which coincides with the lines $\phi = \text{const}$, is defined. The value $\psi_e$ can be calculated from eq.(1), as

$$
\psi_e = \int \ln v_e^e dr \quad (5)
$$

in the case, when the radial distributions $n(r)$ and $v_i^e(r)$ are known in any "supporting" cross-section. The electron velocity can be calculated as drift velocity:

$$
v_e = V_e = \frac{[E,H]}{H^2}.
$$

Radial plasma density distribution $n(r)$ can be determined from independent probe measurements or with the Stark widening of the line $H_\theta$. Then, the topograms $n(r)$ and $\psi_i(r)$ are resulted from Eqs. (3) and (4), $v_i(r)$ and $v_e(r)$ - from eq.(1).

The important question of calculations is the problem of a calculated topogram accuracy, velocity and density, and it was studied in detail in [4]. This paper showed, that the mistakes appearing in the process of calculation (particularly, of density) are nearly 20-30% in the MHD one. The maximum differences of values of the calculated and experimentally measured densities can be observed in the near-electrode regions, that is connected with breaking an axial-symmetry near the anode (rod anode) as well as with the noticeable perturbation of plasma current when setting the electric and magnetic probes into the near-cathode layer with the thickness of 1.5-2 cm.

3.2 Results of calculations.

The Current Transport Mechanism. The conclusion on the current transport mechanism in the accelerator channels was made on the basis of comparing the velocity projections on current line and electrons on the current line. The calculations showed, that in the channel of QSPA Kh-50 within 200-250 $\mu$s (discharge time - 300 $\mu$s) the ion velocity projection $v_i$ on the current line is 15-30%
larger than that of $v_e$. Such a ratio of electron and ion velocities points out realization mainly the ion current transport in the accelerator channels of QSPA Kh-50.

**Flux Velocity Transition Over The Local Velocity of Signal.** Fig. 4 shows the results of comparing the flux velocity $|v_j|$ and the local signal velocity $C_s$ (lines of the equal ratio $C = |v_j|/C_s$) for one regime of the QSPA Kh-50 operation. The local velocity of a signal is $C_s = \sqrt{C_A^2 + C_T^2}$, where $C_A$ - Alfvén velocity, $C_T$ - sound velocity calculated when considering $T_i + T_e = 20$ eV (it was essentially smaller than $C_A$).

The above-mentioned data show, that switching on the magnetic system $T_A$ in QSPA Kh-50 (Fig. 3) affects the transsignal plasma flow in the accelerator channel. It was shown that when the current $I_{T_e} = (0.1-0.15)I_d$, where $I_d$ is a discharge current, $I_{T_e}$ - current in magnetic system of the $T_e$, passing through the magnetic system $T_e$ QSPA Kh-50, the set on the cathode current vortex escapes, and the current lines between electrodes are radial during 200-250 μs. As it was shown in the calculations, the transsignal plasma flow is preserved in the accelerator channel of the QSPA Kh-50 within this interval of time.

For the QSPA Kh-50 $I_{T_e} = 0$ (Fig. 3) with a current sliding along the outside electrode surface, there is no transition of the plasma flow velocity over the local velocity of a signal over the whole width of the channel. The oversignal plasma flow is observed in the near cathode region at the accelerator outlet. When current is sliding along the surface of the central electrode the line $C = |v_j|/C_s = 1$ is shifted to the outlet of the accelerator, and it is drawn in the flux direction in the central part alone the radius.

We suppose, that one can not observe transition of the flux velocity over the local velocity of a signal all over the channel width in the regions of QSPA operation with the current line sliding along the anode because of peculiarities of potential distribution near the anode. As it follows from the MHD theory [1], to obtain the transsignal plasma flow, the flux pipe must have a variable cross-section, that is, it is narrow at first and then gets wide. In conditions of real experiment with a low temperature of electrons ($T_e = 2-3$ eV), the line of equal potential can be chosen as boundaries of the flux pipe. As it was shown experimentally, with the anode sliding of current, the line of equal potential has a form of a cathode practically in the whole accelerator channel including the region near the outer electrode. Hence, the width of some flux pipes changes slightly along the length of the accelerator channel. In the case of such a geometry of flux pipes, transition of the flux velocity over the local velocity of a signal does not take place. That was presented by the calculation results. The current sliding along the central electrode results in decreasing of the longitudinal velocity component of the ion velocity, and hence, the signal must reach its velocity in the outer part of the accelerator channel.

**Flow Isomagnicity.** According to the determination, the plasma flow is isomagnetic, if: $H/nr = const.$ flux pipes. For current toograms are presented in Fig. 3.d,e,f (mode of operation with radial current line) $H/nr = const$ in the whole volume of the accelerated channel. The values $H/nr$ for the various current pipes occur in the cross-hitched region and have a difference not more than 10-15%. In all other investigated work regimes of accelerators with current sliding along the outside or inside electrodes (see Fig. 3.a,b,c) there is no isomagnetic flow at all. In these cases the values $H/nr$ for various flux pipes can differ each other in twice and more.

**Flow Isoberouly.** In the case of flow isoberouly, the Bernoulli integral

$$U_\|(\psi_i) = \frac{M}{2r^2} n^2 |\nabla \psi_i|^2 + \omega_i (n) + \varepsilon \varphi$$
I

(where \( v_1 \) is a ion flux function, \( \omega_i \) - enthalpy) is a linear function \( \psi_i \) \(^1\). The calculated data show, that for all analyzed work regimes of accelerators with radial current lines the dependence of the Bernoulli truncated integral

\[
U_i^* = \frac{M}{2r^2n^2} |V\psi_i| + e \varphi
\]

on \( \psi_i \) is close to the linear one. If current line sliding along the outside or inside electrodes \( U_i^* \propto \psi_{i}^\alpha \), \( \alpha \approx 0.5 \pm 2 \) (\( \alpha \) is different for different part of the accelerating channel). The function inclination \( U_i^* \) from the linear one may deal with current vortexes creation or current sliding, the essential role in which may belong to the dissipative process (plasma heating [5]) leading particularly to increasing \( \omega_i \) (\( n \)), and which are not taken into consideration when calculating.

4. Parameters of the plasma stream.

Figure 4 shows the time dependencies of the plasma flow velocity, density and power density (near the axis) at the QSPA Kh-50 output (0.7 m from the accelerator) for one of the optimal mode of operation, when quasistationary acceleration exists during 100-150 \( \mu \)s. This mode of operation we obtained when we used additional current in the drift channel for correction of the plasma density radial distribution at the input of the main acceleration channel [6]. Power density calculated as \( P(t) = 0.5M\int n(t)v^3(t) \), We mast note that the time behavior of the main plasma parameters is good correlated with power deposition into accelerator. The plasma stream velocity \( v(t) \) close to the maximum theoretical outlet velocity \( v = \sqrt{2C_A} \) (\( C_A \) - Alfven velocity, calculated bases on the magnetic field and plasma density, measured at input of the accelerating channel) achieved in all mode of operations were current line was radial.

Fig.5. Time dependencies of the plasma stream density (1), velocity (2) and plasma stream power density (3) for \( U_e=12 \) kV (\( I_d=600 \) kA).

On the fig.6 are shown dependencies of the efficiency and thrust of the main accelerating channel. Efficiency calculated as \( \eta = W_{pi} / \int J_{a}(t)U_{a}(t)dt \), were \( W_{pi} = 2\pi \int \rho_{pw}(r)rdr \) is energy content in plasma stream calculated from radial distributions of the plasma energy density \( \rho_{pw}(r) \) measured by small integral calorimeter. Bases on the radial distributions of the plasma stream velocity and density we calculated thrust of the accelerator as \( T = m v \) were \( m = 2\pi \int M_n(r)\psi(r)rdr \) is mass flow rate. As we can see from fig.6 efficiency is near constant \( \approx 80\% \) for discharge current more than 350 kA and thrust increase with increasing of the discharge current as \( T \propto I_d^\beta \) were \( \beta \approx 1.6 \pm 1.8 \). Very important note that this parameters is good correlated with theoretical estimate: thrust \( T \propto I_d^\beta \) and efficiency \( \eta=1-\xi-\theta \) were \( \xi \approx 0.1\)- parameter of exchange, \( \theta \approx 0.1\)- part of plasma stream were pumping to divertor channel in the cathode transformer.
The plasma energy density, measured on the distance from accelerator output z=0.7 m achieved 3 kJ/cm² (in near axis region) and plasma cern diameter was ~ 2 cm. At the distance 1.5 m from accelerator energy density fell down and was 700 J/cm² for U_c = 15 kV (with plasma cern diameter ~ 7-10 cm). In operation regime with U_c = 15 kV the total energy content in plasma achieved ~ 0.5 MJ.

CONCLUSION

The present experiments, carried out in accelerator with active transformers, have shown that a regular plasma flow (with radial current lines) in the main accelerating channel can be achieved when providing the optimal gas supplying from the anode side and choosing the proper values of currents flowing in the magnetic systems of the anode and cathode transformers, as well as choosing the operating conditions for the 1st stage. Under these conditions we succeeded in maintaining the quasistationary plasma generation as long as 150 μs. The plasma streams with the velocity v(t) close to the maximum outlet velocity v = √2C_a(t) was achieved. In the optimal mode of operation (with radial current lines) we obtained isomagnicity, isobernouly, oversignal plasma flow in the main accelerating channel with ion current carried. The efficiency and thrust is good correlated with theoretical estimate. The maximum values of efficiency η ~ 85% and thrust T ~ 25 kN was achieved. The maximum value of plasma stream velocity was 4.10⁷ cm/s. The total energy containment in plasma increased up to 500 kJ and plasma energy density achieved 3 kJ/cm² (close to accelerator output).

References