PLASMA DYNAMICS AND PLASMA-WALL INTERACTION

HIGH-POWER PLASMA DYNAMIC SYSTEMS OF QUASI-STATIONARY TYPE IN IPP NSK KIPT: RESULTS AND PROSPECTS

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This paper is devoted to brief review of main experimental results of investigations of high-power quasi-stationary plasma dynamic systems in the IPP NSC KIPT. In experiments were shown that to received accelerated plasma streams with high value of energy in quasi-stationary modes all conditions on the accelerating channel boundary should be controlled independently. As a results of optimizations of the modes of operation all QSPA active elements quasi-stationary plasma flow in the channel during 480 μs at discharge durations 550 μs was obtained. The plasma streams velocity was close to theoretical limit for present experimental conditions. Plasma streams with maximum velocity up to $4.2 \cdot 10^7$ cm/s and total value of energy containment in the stream 0.4…0.6 MJ were received. The main properties of compression zone formation in the plasma streams generated by magneto-plasma compressor in quasi-stationary modes were investigated. In experiments were shown that initial conditions, namely residual pressure in the vacuum chamber made a big influence on the value of plasma density in compression zone. Compressive plasma streams with density $(2…4) \cdot 10^{18}$ cm^{-3} during 20…25 μs at discharge duration 10 μs were obtained. This value of plasma density is close to theoretical limit for present experimental conditions.

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INTRODUCTION

Interest for study the fundamental features of high-power plasma dynamic quasi-stationary system and plasma streams with unique complex parameters, namely: time of generation, energy, density and ion energy, is caused by their application in different fields such as development of radiation sources, plasma surface interactions, simulation of space events, plasma technology, etc.

The principles of quasi-stationary plasma flow in profile channel were formulated by prof. Morozov A.I. [1]. It was proposed to made profiled channel (Fig. 1) with discharge current flowing in radial direction and to inject the working gas.

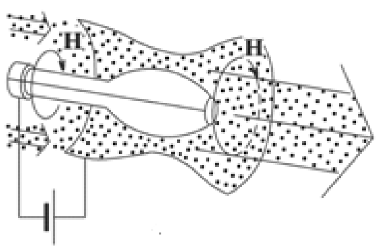


Fig. 1. Scheme of quasi-stationary plasma-dynamic system

In this case plasma will be accelerated under Ampere force $F_z = \frac{1}{c}[j_r \times H_\theta]$. The maximum plasma stream velocity can be estimated from Bernoulli equation [2] as $v_{max} = \sqrt{2}C_{A0}$, where C_{A0} – Alfven velocity in the channel entrance. In first experiments [3] the plasma stream parameters are found to be so far from expected. Because of that further theoretical investigations, under prof. A.I. Morozov management, and numerical calculations, under prof. K.V. Brushlinskij, were performed. The main results of theoretical and numerical investigations can be summarized as follows: transition to ion current carry in the channel and two stage acceleration to avoid the influence of ionization zone instability on the plasma flow in the main accelerating channel [4]. Theoretically it was shown possibility to realize two modes of plasma dynamic system operation: accelerating mode of operation when input electrical energy transforms mainly to the plasma stream kinetic energy and compression mode of operation when energy transforms mainly to thermal energy of compression zone.

REALIZATION OF THE MAIN PRINCIPLES IN QUASI-STATIOARY PLASMA ACCELERATORS AND RESULTS OF PLASMA FLOW INVESTIGATIONS

The experimental investigations were started in the Institute of Plasma Physics of NSC KIPT under V.I. Tereshin’s management. The main principles of quasi-stationary plasma acceleration were realized in two experimental installations with road electrodes [5] and with active magneto-plasma transformers [6] as well. Both these accelerators were manufactured in two stage scheme. The main attention in experiments was paid to investigation of electrical current spatial distributions in accelerating channel. As it was mentioned above, the current should flow in radial direction for effective plasma acceleration. A number of small in size (maximum diameter 5 mm) magnetic probes were used for electrical current spatial distributions measurements.

QUASI-STATIONARY PLASMA ACCELERATOR WITH ROAD ELECTRODES

The QSPA with road electrodes (Fig. 2) has cylindrical anode with diameter 50 cm and length

80 cm. Profile cathode with maximum diameter 32 cm and length 60 cm. The first stage consists of 4 small plasma accelerators with solid electrodes and anode diameter 8 cm. Working gas, hydrogen, flows from first stage and feels up main accelerating channel and outer anode volume. This gas is used for ion current carry. In some experiments outer plastic glass screen was used to keep gas close to anode surface and to support discharge current by additional ions. Capacitor bank with capacity 3600 μF and maximum voltage 9 kV was used as a power supply system. Maximum value of discharge current in the main accelerating channel was 400 kA. The accelerator was installed into vacuum chamber with diameter 100 cm and length 400 cm.

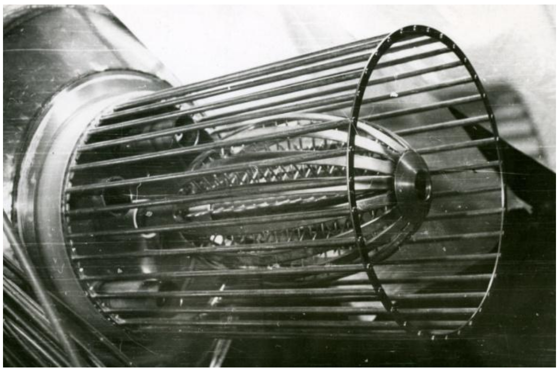


Fig. 2. General view of the QSPA with road electrodes

Experimental investigations showed that electrical current spatial distributions strongly depend on channel boundary conditions, input part, anode and cathode surfaces also. Spatial distributions of current and electrical potential in accelerating channel of QSPA with road electrodes in optimal mode of operation with outer screen are shown in Fig. 3 [7].

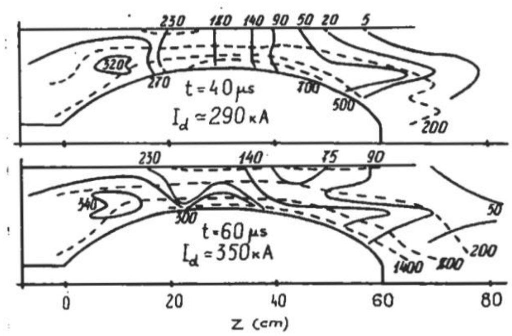


Fig. 3. Spatial distributions of current and potential in accelerating channel of QSPA with road electrodes

As we can see from this figure discharge current flows mainly in radial direction during 40…50 μs. After that current lines sliding along electrodes surfaces is observed with formation of current vortex. Thus, the duration of regular plasma flow, when current flows mainly in radial direction, is about 20…30 μs and it is equal to 2…4 flight-time of particles along the acceleration channel. In non optimal mode of operation, namely without outer screen, when decreased discharge support by ions from anode surface the duration of regular plasma flow decreased to 10 μs or not set in at all.

Two different types of current vortex were discovered: in input channel cross section and based on cathode surface. The nature of these vortexes is completely different. It was found experimentally that plasma volume between first and second stage of accelerator is equipotential. It means, that plasma streams generated by input ionization chambers are decelerated and do not reach the main accelerating channel. In this case kinetic energy of plasma streams is transformed to energy of magnetic field in current vortex and partially to plasma thermal energy. Electron temperature in the input part of accelerating channel was estimated from volt-ampere characteristics of double electric probe and it was about 10…30 eV. At the same time in other parts of plasma stream electron temperature was about 2…4 eV.

Experimentally it was discovered that during plasma flow establishment (first 10…15 μs) there is non equipotential thing plasma layer (0.5…1 cm) close to the cathode surface. Tangential to cathode surface component of electric field is generated. Thus, in crossed tangential electric field and azimuthal magnetic field plasma drifts to cathode volume. Plasma density in cathode volume are reach value (2…3).10^{17} cm^{-5} during first 10…15 μs of discharge. At the same time, density in accelerating channel is about 10^{15} cm^{-3}[8]. After that short period of time tangential to cathode surface component of electric field disappears, drift into cathode volume became stopped and plasma along with frozen magnetic field moved back to accelerating channel forming the current vortex.

Based on experimental results of investigations of plasma flow in accelerating channel formed by road electrodes one possible to made several important conclusions: 1 – it is possible to receive regular plasma flow in accelerating channel in quasi-stationary regimes; 2 – the duration of regular plasma flow strongly depends on accelerating channel boundary conditions; 3 – to receive regular plasma flow in accelerating channel during several tens or several hundreds μs the channel boundary conditions should be controlled independently.

QUASI-STATIONARY PLASMA ACCELERATOR WITH ACTIVE MAGNETO-PLASMA ELECTRODES-TRANSFORMERS

The QSPA Kh-50 with active magneto-plasma electrodes-transformes was designed, manufactured and built in IPP NSC KIPT [6]. The block diagram of full-scale QSPA is shown in Fig. 4.

The accelerating channel of QSPA Kh-50 is formed by active anode transformer with average diameter 50 cm and length 80 cm. Anode transformer contains 10 anode ionization chambers which support discharge by ions to supply ion current carry in the channel and independent magnetic system which forms magnetic emitting surface. Profiled part of cathode transformer has maximum diameter 32 cm and length 60 cm. The first stage of accelerator consists of 5 input ionization chambers. First and second stages are separated by drift chamber with length 60 cm. All accelerator systems powered by capacitor banks with total energy up to 4 MJ. Maximum value of discharge current in the main accelerating channel was about 1 MA. The accelerator was installed into the vacuum chamber with diameter 1.5 m and length 10 m.

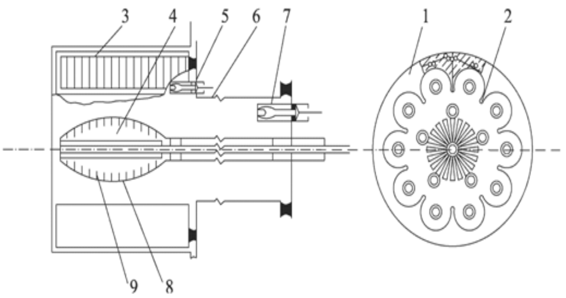


Fig. 4. The block diagram of full-scale QSPA:
1 − anode collector; 2 – anode collectors;
3 – independent anode magnetic system; 4 – cathode transformer; 5 – anode ionization chambers (AIC);
6 – drift channel; 7 – input ionization chambers (IIC);
8 – independent cathode magnetic system;
9 – electron emitters

It was found that plasma flow parameters strongly depend on modes of operation of each active element of full-scale QSPA, namely:

- IIC (five IICs) mass flow rate, discharge current, time of discharge ignition;
- AIC (ten AICs) mass flow rate, discharge current, time delay of discharge start);
- Start time of discharge in each element;
- Current value in the magnetic system of anode transformer;
- Value and direction of current in the magnetic system of cathode transformer.

The spatial distributions of electrical current in accelerating channel of full-scale QSPA in optimal mode of operation for all active elements of accelerator are presented in Fig. 5 [9]. As we can see from this picture current flows mainly in radial direction during 200…250 μs. If even one active element of QSPA operated in non-optimal mode, regular plasma flow in accelerating channel was not observed. For example, if magnetic system of cathode transformer is switched off and plasma can drift into cathode volume, current vortex close to cathode surface is generated and discharge current is slighting along the cathode surface. Current vortex in input part of the accelerating channel is caused by deceleration of plasma streams, generated by IIC. Spatial distributions of plasma potential and radial distributions of plasma density were measured in drift chamber. It was shown that practically all volume of drift chamber is equipotential and plasma passed from IIC to main accelerating channel in thin layer close to the drift chamber wall. In this case radial distribution of plasma density do not feet theoretical dependence $n \sim 1/r^2$.

In most experiments the time dependence of discharge current was close to sinusoidal or to critical apeoridical discharge wave form.

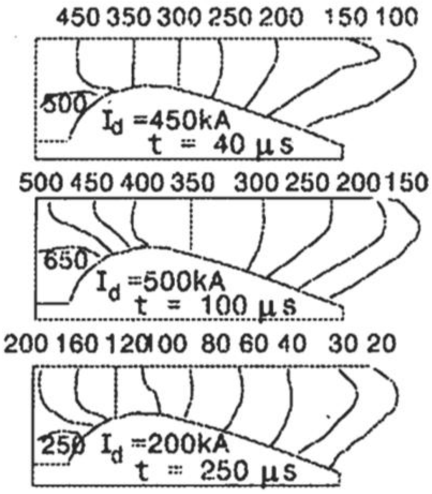


Fig. 5. Spatial distributions of electrical current in accelerating channel of QSPA with magneto-plasma electrodes-transformers

The effective method for correction of plasma density radial distribution was realized [10]. It was proposed to generate Ampere force by applying additional discharge between the drift chamber wall and cathodes of each IIC. The principle scheme of Ampere force generation is presented in Fig. 6.

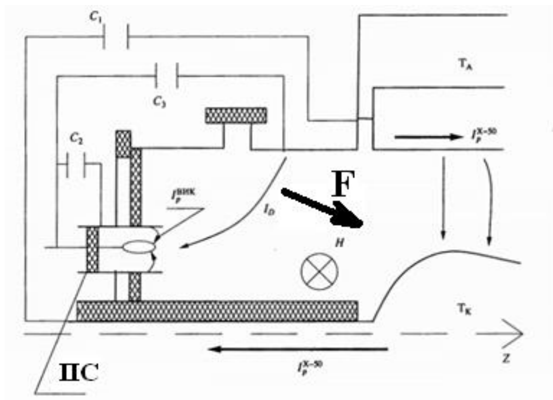


Fig. 6. The principle scheme of additional Ampere force generation in drift chamber

The current of additional discharge and magnetic field of the main discharge current produced Ampere force that moved plasma both to the accelerating channel and to the axis of system. As result of additional correction discharge the regular plasma flow without any current vortex was obtained in the main accelerating channel of the QSPA with magneto-plasma electrodes-transformes during 230…250 μs (Fig. 7). In this mode of operation radial distribution of plasma density in the input part of accelerating channel is close to theoretical dependence $n \sim 1/r^2$.

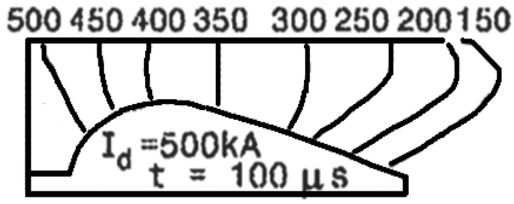


Fig. 7. Spatial distributions of electrical current in accelerating channel of QSPA with magneto-plasma electrodes-transformers with additional correction discharge

However in some cases, it is important to form const discharge current profile during several hundreds μs. The power supply system of the main discharge of QSPA consists of 6 parts and each part can be switch on in different time moments. Example of adjusted ignition of each part of battery and time dependence of discharge current are shown in Fig. 8. The discharge current is changed very slowly during 250…300 μs.

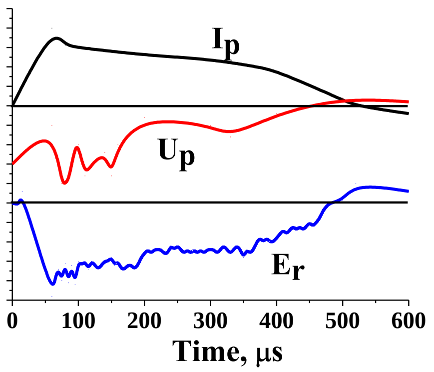
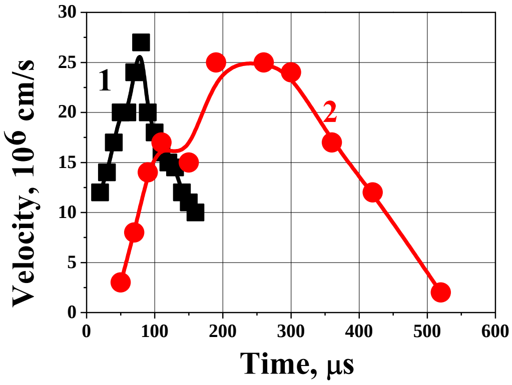


Fig. 8. Time dependences of discharge current I_p, discharge voltage U_p and radial component of electric field E_r

Several separate peaks corresponding to switching on the different parts of capacitor banks are observed on discharge voltage wave form. At the same time wave form of the radial component of electric field, measured in the central part of accelerating channel, is very close to wave form of discharge current. It shows that electric field in plasma stream has Lorentz nature.

Important characteristic of the plasma streams, generated by QSPA, is stream velocity. As follows from theoretical estimation the maximal velocity is $v_{max} = \sqrt{2}C_{A0}$, where C_{A0} – Alfven velocity in the channel entrance. Fig. 9 presents dependences of plasma stream velocity for two different QSPA modes of operations [11]: short pulse with discharge duration 300 μs (1) and long pulse with discharge duration 550 μs (2). Points indicate the results of measurements and curves represent the value of calculated maximum velocity, based on measured values of magnetic field and plasma density in the input part of accelerating channel. As we can see experimentally measured velocity and calculated maximal velocity are in good agreement. Thus, QSPA with magneto-plasma electrodes-transformers generated the plasma streams during 20…30 μs in short pulse mode of operation (that corresponds to 10…15 times of particle flights along accelerating channel) and during 300…350 μs



(~ 100…150 flight times) in long pulse mode of operation.

Fig. 9. Time dependencies of plasma stream velocity. 1 – short pulse mode of operation; 2 – long pulse mode of operation

Based on obtained experimental data one possible to conclude that accelerating asymptotic of Bernoulli equation has been realized experimentally in quasi-stationary mode.

PLASMA FLOW IN MAGNETO-PLASMA COMPRESSOR

As follow from Bernoulli equation the maximum value of plasma density in compression zone can be estimated as:

$$n_{max} = n_0 \left[(\gamma - 1) C_{A0}^2 / C_{T0}^2 \right]^{\frac{1}{\gamma - 1}},$$

where n_0 – initial density (concentration) of working gas; γ – adiabatic coefficient, C_{A0} and C_{T0} Alfven and thermal velocity in the input part of magnetoplasma compressor (MPC) channel respectively. As follow from theoretical investigations [2] the average width and radius of MPC channel should decreased along axis. Such magneto-plasma device was designed and investigated [12]. The general view of MPC is presented in Fig. 10. The MPC channel forms by solid conical cathode and roads conical anode with diameter in output part 8 cm. The total channel length is 12 cm. Capacitor bank with maximum voltage 25 kV was applied as power supply system. MPC was installed into vacuum chamber with diameter 40 cm and length 200 cm. Maximum value of discharge current ~ 600 kA and discharge duration 10…12 μs. The helium was used as working gas and all experiments were carrying out with residual gas in vacuum chamber under different pressures.

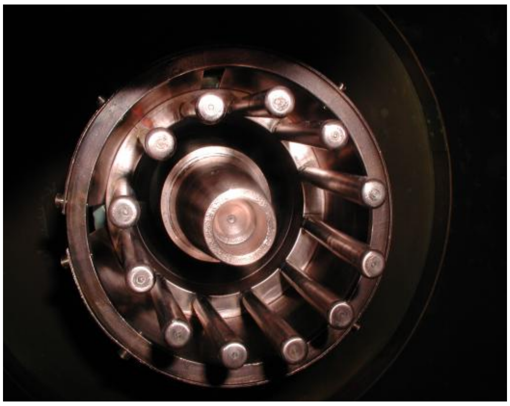


Fig. 10. General view of MPC

The main attention in present experiments was paid to investigation of spatial distributions of electrical current that flows outside the channel, in plasma stream, generated by MPC [13]. Based on experimentally measured distributions of electrical current the spatial distribution of electro-magnetic force was calculated. The example of spatial distribution of current in plasma stream for initial pressure of helium 2 Torr are presented in Fig. 11.

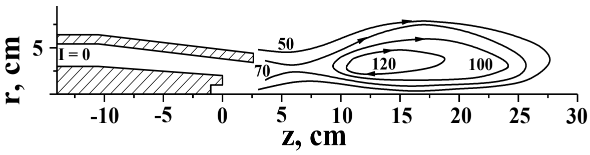


Fig. 11. Spatial distribution of electric current in plasma stream, generated by MPC

Current displacement from the axis region is observed close to the MPC output. The toroidal current vortex is generated in plasma stream at the distance 10…20 cm from MPC output. At distance 4…7 cm from MPC output the radial component of current density has a positive sign. In this case the longitudinal component of electromagnetic force decelerates plasma stream in this region. At the same time radial component of electromagnetic force moves the plasmas stream to axis and forms compression zone.

Fig. 12 presents temporal dependencies of plasma stream density at the distance of 5 cm from MPC output for two different initial gas pressures. It was found that compression zone with density $(2…3)\cdot10^{18}$ cm^{-3} developed at the MPC output and existed during 20…25 µs (discharge duration is 10 µs). It means that compression realized during 20…30 times of particles flight along the MPC channel. The maximum value of plasma density in compression zone can be estimated from Bernoulli equation and for present experimental conditions is about $1.8\cdot10^{18}$ cm^{-3}. The value of plasma temperature in compression region, as estimated from pressure balance equation, is about 60...120 eV. Thus, compression asymptotic of Bernoulli equation has been realized experimentally in quasi-stationary mode. With increasing initial gas pressure in vacuum chamber up to 10 Torr compression zone formation was not observed.

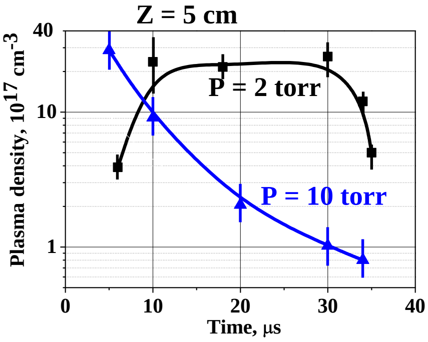


Fig. 12. Time dependencies of plasma stream density at distance 5 cm from MPC output

CONCLUSIONS

The main principles of quasi-stationary plasma flow in profiled channels were realized experimentally. Accelerated plasma streams with velocities close to the theoretical limits were obtained during 100…150 times of particle flow along the channel. So, the accelerating asymptotic of Bernoulli equation has been realized experimentally in quasi-stationary mode. Dynamics of the plasma flow in profiled channel was investigated. It was shown that boundary conditions in accelerating channel should be controlled independently to achieve regular plasma flow, with radial current and without potential jumps near the electrodes. Current vortexes near the cathode and in the entrance of accelerating channel were discovered. The reasons of current vortexes formation were investigated and methods for it's suppression were proposed. In optimal QSPA mode of operation the plasma streams with velocity up to $(4…4.2)\cdot10^{7}$ cm/s, energy density in axis region 25…30 MJ/m^2 and energy content in plasma stream of 0.4…0.6 MJ were obtained.

The dynamics of compression zone formation was investigated. It was shown that electrical current and electromagnetic force spatial distribution strongly depend on initial experimental conditions, namely working gas pressure in the vacuum chamber. As it was demonstrated in experiments, plasma stream decelerated in the compression zone and plasma kinetic energy transformed into the thermal energy. The plasma density and temperature achieved $(2…4)\cdot10^{18}$ cm^{-3} and (60…120) eV in steady-state mode. It is close to the theoretical predictions for chosen experimental conditions. The compression zone with plasma density close to theoretical limit for present experimental condition existed during 20…25 µs, that equal to 20…30 particle flight-times along the MPC channel. Thus, the compressing asymptotic of Bernoulli equation has been realized experimentally in quasi-stationary mode.

Obtained results are in particular importance for applications of QSPA in fusion relevant studies on plasma-surface interactions [14-16] and for technological applications of compressed plasma [17, 18].

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МОЩНЫЕ КВАЗИСТАЦИОНАРНЫЕ ПЛАЗМОДИНАМИЧЕСКИЕ СИСТЕМЫ В ИФП ННЦ ХФТИ: РЕЗУЛЬТАТЫ И ПЕРСПЕКТИВЫ

Д.Г. Соляков

Работа посвящена краткому обзору основных экспериментальных результатов исследования мощных квазистационарных плазмодинамических систем в ИФП ННЦ ХФТИ. Показано, что для получения ускоренных потоков плазмы с большим энергосодержанием в квазистационарном режиме необходимо независимым образом управлять условиями на границах ускорительного канала. В результате оптимизации работы всех вспомогательных элементов КСПУ были получены квазистационарные течения плазмы с временем генерации 480 мкс при длительности разряда 550 мкс и скорости генерации, близкой к теоретическому пределу для данных экспериментальных условий. Получены плазменные потоки с максимальной скоростью $4.2 \cdot 10^7$ см/с и полным энергосодержанием 0.4…0.6 МДж. Исследованы основные закономерности формирования компрессионных потоков плазмы, генерируемых в квазистационарном режиме магнито-плазменным компрессором. Показано, что начальные условия (в частности, давление рабочего газа) оказывают существенное влияние на плотность плазмы в зоне сжатия. Получены самосжимающиеся потоки с плотностью $(2…4) \cdot 10^{18}$ $см^{-3}$, близкой к теоретическому пределу для данных экспериментальных условий. Время существования зоны компрессии составляло 20…25 мкс при длительности разряда в МПК 10 мкс.

ПОТУЖНІ КВАЗІСТАЦІОНАРНІ ПЛАЗМОДИНАМІЧНІ СИСТЕМИ В ІФП ННЦ ХФТІ: РЕЗУЛЬТАТИ ТА ПЕРСПЕКТИВИ

Д.Г. Соляков

Робота присвячена короткому огляду основних експериментальних результатів дослідження потужних квазістаціонарних плазмодинамічних систем в ІФП ННЦ ХФТІ. Показано, що для отримання прискорених потоків плазми з великим енерговмістом у квазістаціонарному режимі необхідно незалежним чином керувати умовами на межах прискорювального каналу. У результаті оптимізації роботи всіх допоміжних елементів КСПП були отримані квазістаціонарні течії плазми з часом генерації 480 мкс при тривалості розряду 550 мкс та швидкістю генерації, близької до теоретичної межі для даних експериментальних умов. Були отримані плазмові потоки з максимальною швидкістю $4.2 \cdot 10^7$ см/с і повним енерговмістом потоку 0.4...0.6 МДж. Досліджено основні закономірності формування компресійних потоків плазми, які генеруються магніто-плазмовим компресором у квазістаціонарному режимі. Показано, що початкові умови, зокрема тиск робочого газу, істотно впливають на густину плазми в зоні стиснення. Отримані самостискаючі потоки з густиною $(2...4) \cdot 10^{18}$ $см^{-3}$, яка близька до теоретичної межі для даних експериментальних умов. Час існування зони компресії становив 20...25 мкс при тривалості розряду в МПК 10 мкс.