MHD CHARACTERISTICS OF COMPRESSION ZONE IN PLASMA STREAM GENERATED BY MPC

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An investigation of local MHD plasma parameters in flow and characterizations of plasma streams, generated by different types of plasma accelerators and magneto-plasma compressors, is one of actual and important from point of view basic plasma dynamics research and plasma applications in different technologies. The present paper devoted to analysis of magneto-hydrodynamic characteristics of the plasma stream generated by the MPC compact geometry. Such important parameters as spatial distributions of electric current and spatial distribution of electromagnetic force in plasma stream, plasma density and velocity in compression zone have been investigated.

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INTRODUCTION

As was shown in [1] the average radius and width of plasma flux tube should decrease along tube to achieved compression mode of MPC operation. The process of energy transformation, which passed into MPC channel, can be described by Bernoulli equation $U = \frac{v^2}{2} + \int \frac{dp}{\rho} + \frac{H^2}{8\pi} = const$. According with this equation energy that passed from energy supply system transforms to kinetic energy of plasma stream in MPC channel, then, in the compression zone, kinetic energy should transform to plasma thermal energy and then, when plasma stream passed through compression zone, thermal energy should transform to kinetic energy again.

Maximum value of plasma density in compression zone for compression mode of MPC operation can be estimated, based on Bernoulli equation. For discharge current I_d = 400 kA, initial density n_0=2.10^{16} cm^{-3} maximal density in compression equal n_{max}=(1.4…1.6)·10^{18} cm^{-3}.

In present paper described results of experimental investigations of spatial MHD characteristics distributions in compression zone generated by MPC compact geometry (are/was described).

1. EXPERIMENTAL SETUP

Experiments were caring out in MPC compact geometry [2-3]. The MPC channel was formed by coaxial cooper electrodes. The outer electrode (anode) with outlet diameter 70 mm consists of solid cylindrical part and output rod structure including 12 copper rods with diameter of 10 mm and of 147 mm in length. The solid inner electrode (cathode) has outlet diameter 40 mm. MPC channel width, distance between anode and cathode surface, decreased along axis, thus flux tube geometry correspond to requirement for compression mode of operation.

Condenser bank (90 μF) with voltage up to 25 kV was used as power supply system of MPC discharge. Maximum value of discharge current was 500 kA and half period duration equal 10 μs. The general view of MPC is presented in Fig. 1. MPC was installed into vacuum chamber 40 cm in diameter and 200 cm in length. All experiments were performed in mode of MPC operation in residual Helium with pressure from 0.5 to 10 Torr. All experimental results, described in present paper, were obtained at capacitor voltage 20 kV, discharge current in MPC channel 420 kA.

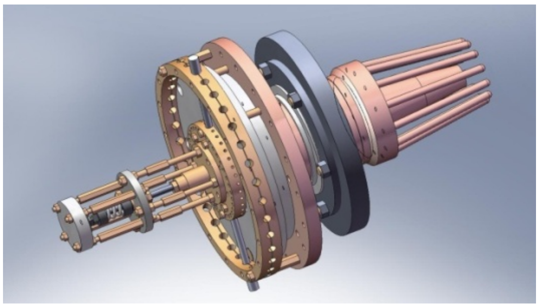

Fig. 1 General view of MPC electrode system

Numbers of magnetic probes were applied for measurements of electric current spatial distribution in plasma stream. Plasma stream density was measured by Stark broadening of different spectral lines. Plasma stream velocity was measured by time flight method between electric probes, installed on different distances from MPC output. Rogowski coil and voltage divider were applied for discharge current and voltage measurements.

2. EXPERIMENTAL RESULTS

To understand process of compression zone formation we have to investigate spatial distributions of electric current and electromagnetic force in plasma stream generated by MPC. Spatial distributions of electric current in plasma stream, generated by MPC was investigated in two modes of operation with residual helium pressure 2 and 10 Torr. Experimentally measured spatial distribution of electric current in plasma stream is presented in Fig. 2 for MPC mode of operation with residual helium pressure 2 Torr.

As we can see from this figure maximum value of electrical current flows outside the MPC channel not more than (15…20) % of total discharge current. Magnetic field displacement from near axis region on distance 5…7 cm from cathode output is discovered. This effect will used for plasma temperature estimation from pressure balance equation. Toroidal vortex of electric current with current value up to 50% of total discharge current has been observed in plasma stream. This vortex generated at distance 12…15 cm from MPC output, when plasma stream passed through compression zone.

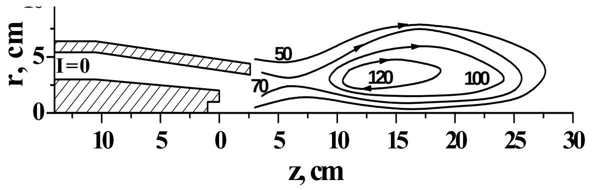

Fig. 2. Electric current spatial distribution in plasma stream. Helium pressure 2 Torr, t = 10 µs

Spatial distributions of electromagnetic force $F = \frac{1}{c}[j \times H]$ in plasma stream were calculated based on electric current distributions. The result is presented in Fig. 3.

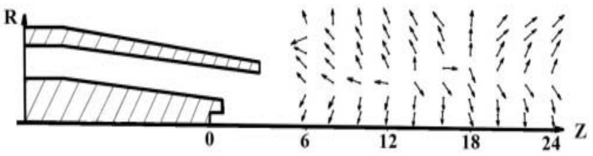

Fig. 3. Electromagnetic force spatial distribution in plasma stream. Helium pressure 2 Torr, t = 10 µs

Each vector shows electromagnetic force direction only and not corresponds to the force value. As we can see plasma stream can be separated on four different areas. The first one is area r<2.5 cm and z<16 cm where plasma stream decelerate and compress in axis direction. The second area r<2.5 cm and z>16 cm is area where plasma stream accelerated, but still compress in axis direction. The third area r>2.5 cm and z<16 cm is area where plasma stream decelerated, but moved in vacuum chamber wall direction. Finally, forth area r>2.5 cm and z>16 cm is area where plasma stream accelerated and moved to vacuum chamber wall direction. Thus, we can expect compression zone formation at distance 5…7 cm from cathode output.

The spatial distribution of electric current in plasma stream changed when residual helium pressure increased up to 10 Torr. The total value of current that flows in plasma stream, increased up to 30% of total discharge current. Magnetic field displacement in near axis region close to MPC output and toroidal current vortex in plasma stream not observed.

Plasma densities in near axis region for MPC mode of operation with pressure 2 and 10 Torr as function of distance from cathode output for time of moment t=10 µs from discharge ignition are presented in Fig. 4.

As we can see from Fig. 4 plasma density strong depends on pressure in vacuum chamber and on distance from cathode output. Maximum plasma density up to (2…3)·10^{18} cm^{-3} was measured at helium pressure 2 Torr at distance 5…7 cm. When helium pressure in vacuum chamber increased up to 10 Torr maximum plasma density decreased up to (6…8)·10^{17} cm^{-3}.

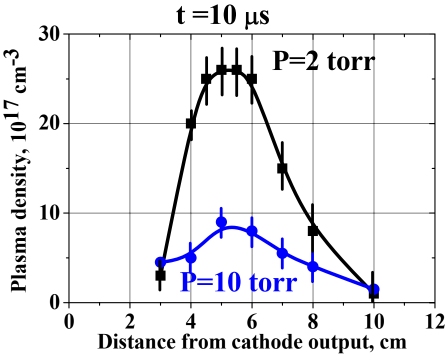

Fig. 4. Plasma density distribution

Time dependencies of plasma density at a distance 5 cm from cathode output are presented in Fig. 5. As we can see from this picture compression zone with density more than 10^{18} cm^{-3} forms starting from t = 8 µs in mode MPC operation with helium pressure 2 Torr. Then, plasma density keeps value (2…3).10^{18} cm^{-3} during 20 µs. It demonstrates quasi-steady-state mode of compression zone formation. Compression zone forms and situated in a distance 3…5 cm from cathode output. In MPC mode of operation with helium pressure 10 Torr compression zone start forms close to cathode output and plasma density decreased with time from (2…4).10^{18} cm^{-3} at time t = 5 µs to (0.5…1).10^{17} cm^{-3} at t = 35 µs.

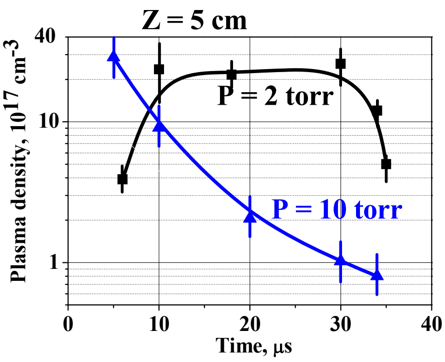

Fig. 5. Time dependencies of plasma density

The velocity of different parts of plasma stream in different distances from MPC output was estimated by time of flight between several double electric probes that was installed along vacuum chamber.

As was discovered the velocity of plasma stream of different parts strong depends on MPC mode of operation and distance from MPC output. For time of moment t = 10 µs from discharge ignition the velocity of plasma stream at distance 1...3 cm from cathode output is equal (2…3).10^7 cm/s. Then, at distance 4…7 cm from cathode output where plasma stream densityreached maximum value stream velocity decreased up to 10^6 cm/s. Then, the stream velocity weakly increased along axis and reach value (8…10)·10^6 cm/s at distance 22…30 cm from cathode output.

3. DISCUSSION AND CONCLUSIONS

As was discovered, the magnetic field displaced from compression zone and plasma density in compression zone reach value (2…3)·10^{18} cm^{-3}. Thus, plasma temperature in compression zone can be estimated, based on pressure balance equation and it value $T = (T_e+T_i)$ = (60…100) eV.

Experimentally there was found that plasma density in compression zone decreased with increasing residual gas pressure, in another words, with increasing initial density (n_0) in the input cross section of MPC channel. As follow from Bernoulli equation maximal value of plasma density in compression zone depends on discharge current and initial density as $n_{max} \sim \frac{I_d^2}{n_0 T_0}$, where T_0 – initial temperature. As we have seen from experimental data, plasma density in compression zone decreased in 3…4 times with increasing initial gas pressure in vacuum chamber in 5 times.

Experimentally there was discovered that plasma stream parameters, namely: the density, the velocity and the magnetic field, strong depend on distance from cathode output. As follow from Bernoulli equation, energy that passed from capacitor bank to MPC channel will transform to three different parts: to kinetic energy of plasma stream, or plasma thermal energy, or the energy of magnetic field, or their mix (Fig. 6).

As we can see plasma accelerated in MPC channel up to velocity v=(2…3).10^7 cm/s, so, the energy transformed to stream kinetic energy. Then, in compression zone the stream velocity decreased up to 10^6 cm/s, or less, but plasma density and temperature increased up to (2…4)·10^{18} cm^{-3} and (60…100) eV respectively, so kinetic energy transformed to thermal energy. When plasma stream passed through compression zone thermal energy transformed to kinetic energy and energy of magnetic field with formation of toroidal current vortex (see Fig. 6). Finally, the energy of toroidal current vortex converted to plasma stream kinetic energy.

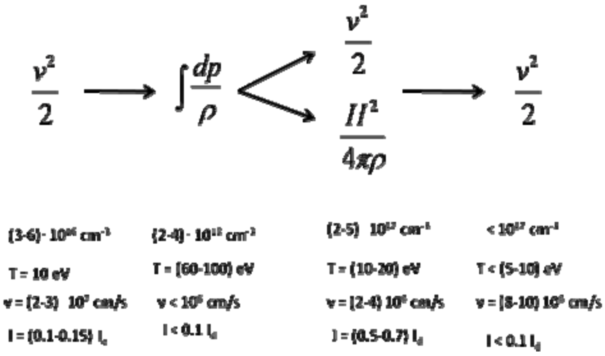

Fig. 6. Energy transformation and plasma parameters for different stream parts

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МГД ХАРАКТЕРИСТИКИ ОБЛАСТИ КОМПРЕССИИ ПЛАЗМЕННОГО ПОТОКА, ГЕНЕРИРУЕМОГО МПК

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Исследование локальных МГД параметров плазмы в потоке и характеристик плазменных потоков, генерируемых различными видами плазменных ускорителей и магнито-плазменных компрессоров, является актуальной фундаментальной задачей физики плазмы. Настоящая работа посвящена анализу магнито-гидродинамических характеристик плазменного потока, генерируемого МПК. Были исследованы такие важные параметры, как пространственные распределения электрического тока и электромагнитной силы в плазменном потоке, плотность плазмы и скорость в зоне компрессии.

МГД ХАРАКТЕРИСТИКИ ОБЛАСТІ КОМПРЕСІЇ ПЛАЗМОВОГО ПОТОКУ, ЩО ГЕНЕРУЄТЬСЯ МПК

В.В. Чеботарьов, Т.Н. Чередниченко, Д.В. Єлісєєв, І.Є. Гаркуша, А.М. Козлов, Н.В. Кулик, М.С. Ладигіна, А.К. Марченко, Я.І. Моргаль, Ю.В. Петров, Д.Г. Соляков, В.В. Стальцов

Дослідження локальних МГД параметрів плазми в потоці та характеристик плазмових потоків, що генеруються різними видами плазмових прискорювачів і магніто-плазмових компресорів, є актуальною фундаментальною задачею фізики плазми. Дана робота присвячена аналізу магніто-гідродинамічних характеристик плазмового потоку, який генерується МПК. Були досліджені такі важливі параметри, як просторові розподіли електричного струму та електромагнітної сили в плазмовому потоці, густина плазми та швидкістьу зоні компресії.