COMPRESSION ZONE FORMATION IN PLASMA STREAMS GENERATED BY MPC DEVICE OPERATING WITH GASES OF DIFFERENT MASS

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This paper presents analysis of compression zone formation in plasma streams generated by compact magnetoplasma compressor operating with argon and helium. The main aim for this investigation is characterization of plasma in compression zone in dependence on initial concentration of working gas. The initial concentration was changed by variation of residual gas pressure in vacuum chamber. The mass flow rate was kept constant. It was possible due to 10 times difference between He and Ar masses. Thus, decrease of residual pressure from 10 Torr for helium till 1 Torr for argon allows keep the mass flow rate in spite the initial density value decreases in 10 times. The temporal and spatial distributions of plasma density were measured in plasma stream and in the compression region in both cases. It was shown with spectroscopy that plasma density in compression region increased up to 3.5 times with decreasing initial concentration in 10 times. The obtained result is in agreement with analytical estimation that follows from the Bernoulli equation. Plasma dynamics in compression region is also discussed.

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INTRODUCTION

Interest for study of compressed magnetized plasma dynamics is caused by dense plasma streams applications for development of radiation sources, studies of fundamental features of plasma surface interaction, simulation of space events accompanied by generation of plasma jets, novel plasma technologies, etc.

As follows from [1] plasma flow in MPC channel and average plasma streams parameters depend on discharge current I_d and mass flow rate $\dot{M} = M_i \frac{\partial n}{\partial t}$, where M_i – ion mass and n – density. Discharge voltage in this case can be expressed as $U_d \sim I_d^3 / \dot{M}$ and average stream velocity is $v \sim I_d^2 / \dot{M}$. Thus, discharge voltage and plasma stream velocity do not depend on initial gas concentration if mass flow rate is kept constant with changing ion mass. At the same time maximum value of plasma density in the compression zone should strongly depend on initial gas concentration. As follow from the 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 MPC channel respectively. For adiabatic compression of atomic gas (γ=5/3) maximum value of plasma density in the compression zone depend on initial concentration as $n_{max} \sim H_0^3 / \sqrt{n_0 T_0^3}$, where H_0 is azimuthal magnetic field produced by discharge current, T_0 and n_0 – temperature and concentration in the input cross section of MPC channel. Temperature T_0 is close to the room temperature for neutral working gas.

First results of experimental investigations of MPC operation with gases of different masses, but with the same mass flow rate are described in [2]. It was shown, that dependencies of energy density on discharge current in near axis region as well as average in time values of plasma stream density and velocity practically not influenced by initial gas concentration. The results of plasma stream density measurements close to the end of MPC electrodes, in compression zone with no time resolution were presented too. Based on these time integrated measurements we can conclude that value of plasma density in near axis region only weakly depends on initial gas concentration. The position of compression zone, where plasma density are maximal, is found to be much more sensitive to the initial concentration. Namely, compression zone is moved to larger distance from MPC channel with decreasing initial working gas concentration.

The main aim of present studies was analysis of spatial and temporal dependencies of plasma stream density in compression zone as function of initial concentration for chosen mass flow rate value.

EXPERIMENTAL INSTALATION AND DIAGNOSTICS

Discharge gap in MPC [3-7] is formed by two conical copper electrodes. Central solid electrode is cathode and outer rod-shaped electrode – anode. The

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anode consists of cylindrical solid section (120 mm in diameter and 145 mm in length) and conical section formed by 12 rods of 10mm in diameter and 147 mm in length, that inclined at 7.5º to the system axis. The cathode consists of cylindrical section (60 mm in diameter and 208 mm in length) and a 120 mm-long solid conical part with output diameter of 30 mm. MPC is installed to vacuum chamber with diameter 42 cm and length 130 cm. Vacuum chamber is pumped by turbo-molecular pump with speed of 500 l/s.

Capacitor bank with capacity 80 µF and maximum voltage 40 kV was used as power supply system for MPC discharge. The main part of present experiments were performed at voltage up to 25 kV. Maximum value of discharge current was 450 kA and discharge half-period 10 µs. Argon and helium with different residual pressure in vacuum chamber was used as working gases. Parameters of plasma streams, generated by MPC were varied by changing of discharge current (voltage on capacitor bank), by sort of working gas and by residual pressure in vacuum chamber.

Rogovski coil and voltage divider were used for discharge current and voltage measurements. Local copper calorimeter was used for energy density measurements in plasma stream. Spectroscopy measurements were performed using visible light spectrometer DFS-452 and monochromator MDR-23 coupled with an electron-optical converter (EOC). The measurements were performed along the plasma stream axis at different distances from the MPC. Spatial and temporal dependencies of electron density were measured from quadratic Stark broadening of Ar II and He II species spectral lines. Stark broadening was calculated from full widths of experimental lines taking into account instrumental and Doppler broadening mechanisms [8, 9]. The spatial resolution in axis region was about 1 cm. Temporal resolution was about 1 µs. Scheme of optical diagnostics is shown in Fig. 1.

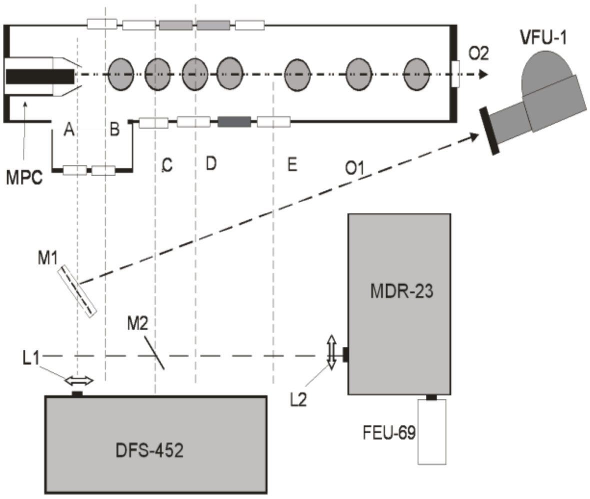

Fig. 1. Scheme of optical diagnostics

Fig. 2 shows typical waveform of discharge current, signal from photodiode in visible wave-range and synchronization peak for switching EOC in different time moments during the discharge in MPC.

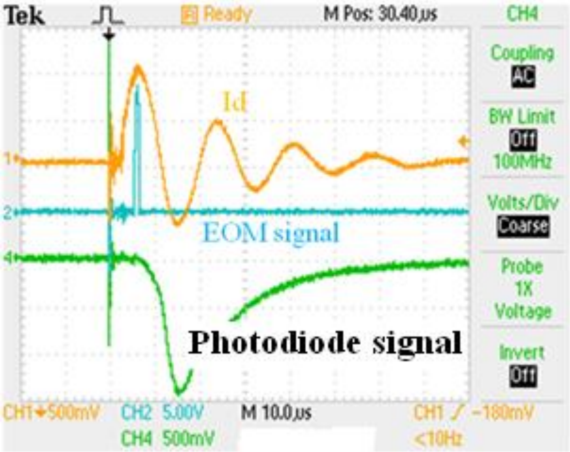

Fig. 2. Typical signals of discharge current, visible emission and EOC synchronization

EXPERIMENTAL RESULTS

As follows from MHD model of plasma flow in MPC channel, the discharge voltage should decrease with increasing mass flow rate and it does not depend on initial working gas concentration. Dependencies of discharge voltage on discharge current for four different initial conditions are shown in Fig. 3. Both variation of residual gas pressure (initial concentration) and sort of working gas has been performed.

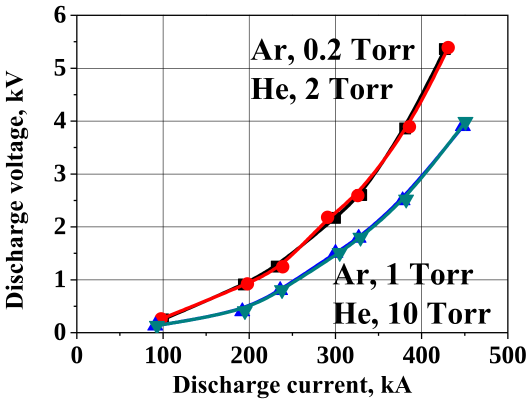

Fig. 3. Voltage-ampere characteristics of discharge in MPC for two different mass flow rates

These dependences were measured for two different mass flow rates: first one is operation with helium (2 Torr) or argon (0.2 Torr) and second is with helium (10 Torr) and argon (1 Torr). Atomic masses of helium and argon differ in 10 times. Thus in such a way, mass flow rate is kept constant if initial concentration (in another words initial residual pressure) differs in 10 times too. As follows from presented measurements, discharge voltage depends on mass flow rate only and it does not influenced by initial working gas concentration if the mass flow rate is the same.

Important differences in plasma stream parameters are observed close to MPC output in near axis region. Fig. 4 presents radial distributions of energy density in plasma stream, that measured at the distance of 6…7 cm.

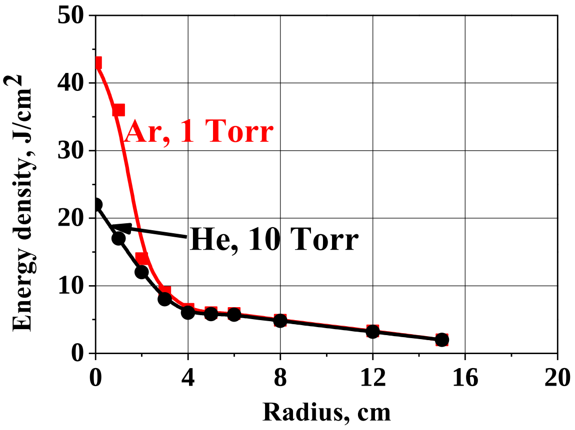

Fig. 4. Radial distributions of energy density in plasma stream for two different initial concentrations

At the periphery (for radius r > 3…4 cm) radial dependences of energy density for different pressures are similar At the same time energy density in axis region for two different initial gas concentrations are differ in 2 times. So, initial concentration made influence on plasma parameters in near axis region with average diameter of 2…4 cm.

Plasma density distributions along the axis are shown in Fig. 5 for time moment 10 μs from the discharge ignition for two different initial concentrations corresponding to the same total mass flow rate. It should be noted that maximum value of plasma density in compression zone increased from $0.9\text{x}10^{18}$ cm^{-3} to $3.3\text{x}10^{18}$ cm^{-3} with decreasing initial concentration in 10 times. As follows from the Bernoully equation [1] maximum value of plasma density in the compression zone should depend on initial concentration as $n_{max} \sim I_d^3 \Big/ \sqrt{n_0 T_0^3}$. The values of discharge current I_d and initial temperature T_0 practically, within accuracy of the measurements, are not changed with variation of initial concentration in present experiments. Thus, maximum value of plasma density increased in 3.7 times and this is in good agreement with the theoretical estimations. It was discovered in previous investigations [2] that the position of compression zone and its size depends strongly on initial gas concentration. Position of compression zone moved from MPC cathode output for 1.5…2 cm and the length of compression zone increased from 3…3.5 cm to 10…12 cm, i.e. in 2.5…3 times with decreasing initial working gas concentration in 10 times.

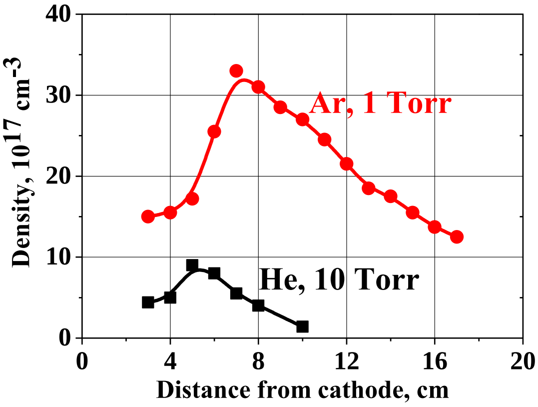

Fig. 5. Plasma density distributions along axis

CONCLUSIONS

Dynamics of plasma streams, generated by MPC operating with gases of essentially different mass is investigated. Helium and argon was used as working gases. The value of residual pressure was varied from 0.2 Torr to 10 Torr to keep total mass flow rate constant, changing initial gas concentration.

It was found that discharge parameters, namely volt-ampere characteristics $U_d(I_d)$ are determined by total mass flow rate only. It was obtained that energy density in plasma stream, measured at the distance of 6…7 cm from MPC output, not depended on initial concentration for radiuses r > 3…4 cm. Energy density in near axis region, on the contrary, strongly influenced by initial concentration. It increased in 2 times with decreasing residual pressure. The average radial dimensions of compression zone estimated from the measured radial distributions energy density in plasma could be evaluated as 2…2.5 cm, and this size is slowly increased with increasing initial concentration.

The value and distributions of plasma density in compression zone are strongly affected by initial concentration. Experimentally it was shown that plasma density in compression region increased in 3.5…3.7 times with decreasing initial concentration in 10 times. This result is in agreement with analytical estimations of plasma density from MHD model.

Experiments demonstrate that region with maximal density has shifted to the distance of 1.5…2 cm from electrodes with decreasing of working gas initial concentration. The length of compression zone increased in 2.5…3 times with decreasing gas concentration in 10 times, but the radial size remained practically unchanged.

Thus mechanism to control the value of plasma density in compression zone and it spatial position and dimension was discovered in present experimental studies that provided the same level of mass flow rate and discharge current values with variation of initial working gas concentration.

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ФОРМИРОВАНИЕ ЗОНЫ КОМПРЕССИИ В ПЛАЗМЕННЫХ ПОТОКАХ МПК ПРИ РАБОТЕ НА ГАЗАХ С РАЗНЫМИ МАССАМИ

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Статья посвящена анализу формирования зоны компрессии в плазменных потоках, генерируемых компактным магнитоплазменным компрессором МПК, используя в качестве рабочего газа аргон и гелий. Основной целью данной работы являлся анализ параметров плазмы в зоне компрессии и их зависимость от начальной концентрации рабочего газа. Начальная концентрация изменялась путем выбора величины давления остаточного газа в вакуумной камере. Массовый расход газа остался постоянным, благодаря 10-кратной разнице масс аргона и гелия. Таким образом, уменьшение остаточного давления с 10 Торр для гелия до 1 Торр для аргона позволяет сберечь массовый расход при уменьшении начальной концентрации в 10 раз. Временные и пространственные распределения электронной плотности плазмы в области компрессии были измерены для двух случаев. Спектроскопические измерения показали, что плотность плазмы в области сжатия увеличилась в 3,5 раза при уменьшении начальной концентрации рабочего газа в 10 раз, что согласуется с аналитическими оценками из уравнения Бернулли. Также представлены исследования динамика плазмы в зоне компрессии.

ФОРМУВАННЯ ЗОНИ КОМПРЕСІЇ В ПЛАЗМОВИХ ПОТОКАХ МПК ПРИ РОБОТІ НА ГАЗАХ З РІЗНИМИ МАСАМИ

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Стаття присвячена аналізу формування компресійної зони в плазмових потоках, що генеруються компактним магнітоплазмовим компресором МПК, використовуючи в якості робочого газу аргон та гелій. Основною метою роботи є аналіз параметрів плазми в зоні компресії та їх залежність від початкової концентрації робочого газу. Початкова концентрація змінювалася за допомогою зміни тиску залишкового газу у вакуумній камері. Масовий розхід газу залишався постійним, завдяки 10-разовій різниці між масами аргону та гелію. Таким чином, зменшення залишкового тиску з 10 Торр для гелію до 1 Торр для аргону дозволяє зберегти масовий розхід в той час як значення початкової концентрації зменшується в 10 разів. Часові та просторові розподіли електронної густини плазми вимірювались в зоні компресії для обох випадків. Часові та просторові розподіли густини плазми були виміряні в плазмовому потоці та зоні компресії обох випадках. Спектроскопічні вимірювання показали, що електронна густина плазми в зоні компресії збільшується в 3,5 рази при зниженні початкової концентрації в 10 разів, що узгоджується з аналітичними оцінками з рівняння Бернуллі. Також досліджувалася динаміка плазми в зоні компресії.