ENERGY CHARACTERISTICS OF PLASMA STREAMS, GENERATED BY MPC

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In present paper, results of experimental investigations of energy characteristics of plasma stream, generated by magnetoplasma compressor (MPC) are presented. It is shown that total energy contained in the plasma stream strongly depends on the discharge current, mass flow rate and sort of working gas. Radial distributions of energy density in plasma streams for different MPC modes of operations and energy transfer efficiency from the acceleration channel to the plasma stream are investigated.

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INTRODUCTION

Investigations of dense magnetized plasma of different gases are important for various scientific and technological applications such as generation and acceleration of plasma streams, testing of fusion reactor materials with high energy and particle loads etc. Dense plasma is especially attractive object of investigations and development of efficient sources of EUV radiation [1]. From the point of view optimization of plasma source operation regimes for lithography applications, achievement of maximal intensity of EUV radiation in the characteristic wavelength of 13.5 nm is important [2, 3].

The present investigations are devoted to analysis of the basic energy characteristics of plasma streams generated by magnetoplasma compressor, which operates with argon. In some experiments helium has been applied as working gas. The main aim of these researches is to analyze the energy characteristics of plasma streams in dependence on discharge current, mass flow rate and residual gas pressure.

1. EXPERIMENTAL DEVICE AND DIAGNOSTIC EQUIPMENT

MPC accelerating channel (Fig. 1) consists on copper coaxial electrodes: outer multiroad anode and the inner cathode. The anode consists of two parts. First one is a solid cylindrical part with diameter 120 mm, length 145 mm. Second part is conical, it consists of 12 rods with diameter of 10 mm each and length 147 mm. Design of MPC device is described in detail in [4-7].

MPC has been installed into vacuum chamber with diameter of 45 cm and length of 200 cm. Camera is pumped by the turbo-molecular pump TMN-500.

Power supply system consists from capacitive bank (90 μF and a maximum voltage of 30 kV) and vacuum discharger.

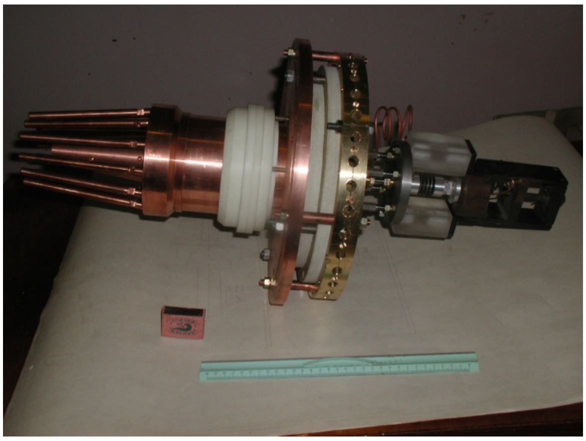

Fig. 1. General view of MPC plasma source

Experiments were carrying with helium and argon under a residual pressure varied in the range of 0.5…10 Torr. Discharge current and discharge voltage were measured by Rogowski coil and voltage divider, respectively. Movable copper calorimeter with diameter of 5 mm was installed at the distance of 11 cm from the MPC output, i.e. close to the compression zone. Discharge current and voltage measurements were used for estimation of discharge efficiency.

2. EXPERIMENTAL RESULTS

Dependencies of plasma stream energy density in near axis region on the discharge current are presented in Fig. 2 and 3 for two MPC modes of operations.

As it is seen from Fig. 2, maximum energy density achieved 45…47 J/cm^2 in MPC mode of operation with argon with pressure of 0.5 Torr and discharge current of 400 kA. In MPC mode of operation with helium with pressure 5 Torr, total mass flow rate is kept the same, by means of initial gas pressure increase in 10 times. Maximum value of energy density in this case achieved 40 J/cm^2 at discharge current of 370 kA. Generally, the dependencies of plasma stream energy density for both experimental conditions are close one to another.

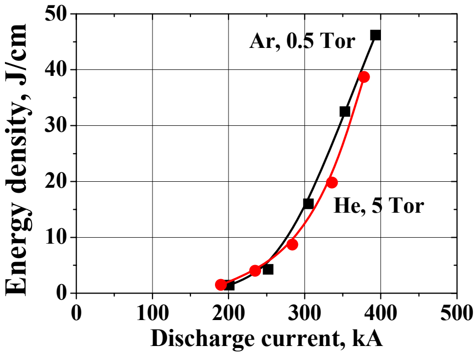

Fig. 2. Energy density in the plasma stream vs. discharge current

When mass flow rate and initial gas pressure were increased in two times, i.e up to 1 Torr for argon and 10 Torr for helium correspondingly, the dependencies of plasma stream energy density on discharge current became essentially different. As it is seen from Fig. 3, maximal value of energy density reaches 40 J/cm^2 in MPC mode of operation with helium at the discharge current of 400 kA. In argon plasma stream energy density decreased up to 20 J/cm^2 at the same discharge current of 400 kA. Plasma stream energy density in the case of helium increased in two times faster with increasing discharge current in comparison with argon plasma. So, with growing residual gas pressure and mass flow rate the dependencies of energy density became different.

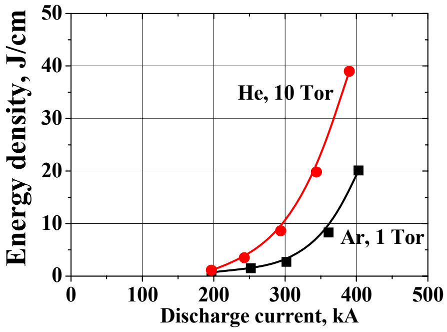

Fig. 3. Energy density in the plasma stream vs. discharge current

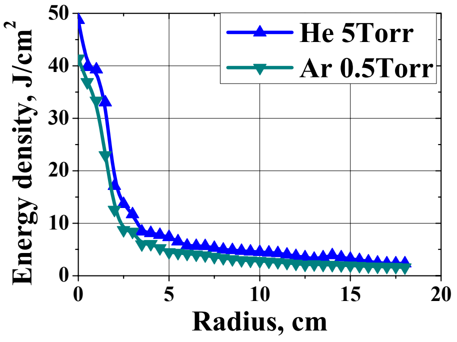

Fig. 4. Radial distributions of energy density in the plasma stream

Fig. 4 sows the radial distributions of plasma stream energy density in MPC mode of operation with low values of mass flow rate and residual gas pressure. As follows from performed studies, the energy density distributions are not depended on residual gas pressure (initial density) at present value of mass flow rate. Average radius of compression zone, estimated as half-width of energy density radial distribution is about 2…2.5 cm.

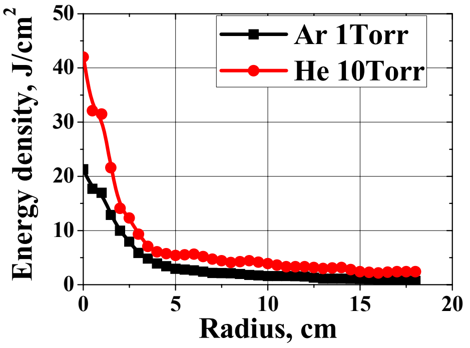

Fig. 5. Radial distributions of energy density for increased gas pressure

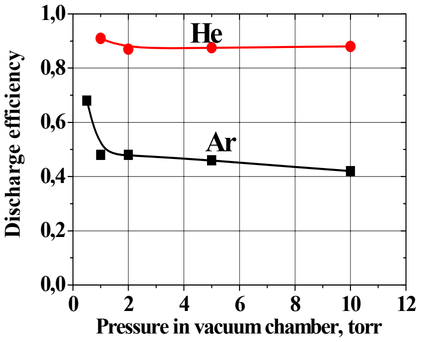

Fig. 6. Discharge efficiency as function of residual gas pressure

Energy density radial distributions for higher value of mass flow rate and residual gas density (helium – 10 Torr, argon – 1 Torr) are presented in Fig. 5. Maximum difference in radial distributions are observed in paraxial area with $r < 2.5…3$ cm. Average radius of compression zone in this case is also about 2…2.5 cm. So, it does not depend on mass flow rate and initial density for present experimental conditions.

The discharge efficiency has been calculated as:

$$\eta = \frac{2\pi \int \rho(r) r dr}{\int I(t)U(t)dt}$$

where ρ *(r)* - energy density in plasma stream, *r* - radius, *I (t)* and *U (t)* discharge current and discharge voltage respectively. Fig. 6 presents dependencies of discharge efficiency as a function of initial density (residual pressure).

Thus, in present experimental conditions, discharge efficiency weakly depends on residual pressure, for pressure range of 2…10 Torr. It reaches value of 0.45…0.5 for argon and achieves 0.9 for helium.

For smaller pressures, discharge efficiency in argon increases up to 0.7 with argon pressure decrease up to 0.5 Torr, but in this case strong electrode erosion is initiated.

CONCLUSIONS

The energy characteristics of plasma streams generated by MPC are investigated. Plasma streams with energy density in near axis region up to 50 J/cm^2 and total energy content of 5.2 kJ are generated. Energy density in plasma stream is found to be not depended on residual pressure (initial density) at small mass flow rates. When mass flow rate increases twice the energy density became strongly depended on initial gas density. It is shown that average radius of compression zone is not influenced by mass flow rate and initial density for present experimental conditions. Discharge efficiency determined essentially by sort of working gas and in pressure range of 2…10 Torr it reached values of 0.9 for helium and 0.45…0.5 for argon respectively.

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ЭНЕРГЕТИЧЕСКИЕ ХАРАКТЕРИСТИКИ ПЛАЗМЕННЫХ ПОТОКОВ, ГЕНЕРИРУЕМЫХ МПК

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Представлены результаты экспериментальных исследований энергетических характеристик плазменных потоков, генерируемых магнитоплазменным компрессором (МПК). Показано, что полная энергия в плазменном потоке существенно зависит от разрядного тока, массового расхода и сорта рабочего газа. Также исследовано радиальное распределение плотности энергии в плазменном потоке и коэффициент передачи энергии от ускорительного канала в плазменный поток в разных режимах работы МПК.

ЕНЕРГЕТИЧНІ ХАРАКТЕРИСТИКИ ПЛАЗМОВИХ ПОТОКІВ, ЯКІ ГЕНЕРУЄ МПК

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

Представлено результати експериментальних досліджень енергетичних характеристик плазмових потоків, що генерує магнітоплазмовий компресор (МПК). Показано, що повна енергія в плазмовому потоці значним чином залежить від розрядного струму, масової витрати та сорту робочого газу. Також було досліджено радіальний розподіл густини енергії в плазмовому потоці і коефіцієнт передачі енергії від розрядного каналу в плазмовий потік в різних режимах роботи МПК.