NUMERICAL SIMULATION OF PULSED PLASMA THRUSTER WITH A PREIONIZATION HELICON DISCHARGE

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The major electrical characteristics of pulsed coaxial magneto-plasma accelerator with a capacitive power source are calculated on the basis of approximate mathematical model of pulsed plasma thruster, preionization system of working gas with a helicon discharge and multiparametric optimization of CMPA by methods of computational experiment. The main parameters of the RF source and physical characteristics of argon plasma are presented. Initial assessments are conducted prior to plasma acceleration using helicon preionization source and main characteristics of coaxial magneto-plasma accelerator.

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INTRODUCTION

This work is devoted to the development of the perspective electrodeless plasma thruster (EPT) with a high-frequency ionization which is called as a helicon engine [1 - 5]. As we know [1 - 7], the main advantages of this kind of engine is quite high (compared with another EPT) resource of life, the possibility of using the different working fluids. Such types of helicon plasma sources can be widely used for plasma interaction studies with a substance in the systems of magnetic and magneto-inertial confinement of hot plasma [8 - 11]. Comparing with another reviewed EPT can be used as the engines for correction and orientation of geostationary and low orbital (weight less than 100 kg) spacecrafts and sustainer rocket motor as well. The radio frequency (RF) discharge is used for the preionization (helicon preionization source) for this type of engine, placed in an external magnetic field. The efficiency, high reliability and low cost of such charges allow using them in the field of accelerator technology, in different plasma and vacuum technology and etc. with a high degree of effectiveness. At the same time there is no contact of plasma with metal electrodes and there is quite low electron temperature and low plasma potential relative to the walls, which limits the discharge.

1. DESCRIPTION OF THE PROBLEM

An inductor is a component of CMPA intended for decreasing a thermal interaction of plasma with the walls of the working channel of CMPA. In our case, the inductor can be electrically isolated from the accelerator and perform two functions: 1) creating of a cylindrically symmetric compact plasmoid (disc) that solves a problem of an azimuthal instability; 2) the preliminary acceleration and throwing into the CMPA channel plasma.

We briefly describe the principle of operation of the proposed CMPA. Short circuit through the conducting plasma (geometrically disc) takes place after applying a voltage U_0 from the capacitive power supply on the central and cylindrical electrodes of CMPA. This plasma disc is created by the breakdown of a gas (after voltage U_0 supply) and interaction of impulse current of inductor with a circular whirling current in a plasma formation it influences on appearing the electromagnetic force which affects upon the plasma and providing its initial acceleration and inflowing to the acceleration channel of CMPA. Then plasmoid electromagnetically compressed and accelerated in the direction of the axis of symmetry. At the same time an electrodynamic acceleration of plasma in the channel of CMPA is based on interaction (described by the Ampere law) of the magnetic field of the electric circuit with current-carrying plasma.

The creation of an experimental stand for research of electrophysical properties of CMPA is very expensive, and the creation of a model can be considered as the original problem. The pulsed plasma thruster and preionization system for gas based on helicon discharge (the pulsed RF-preionization discharge) will be examined in the framework of an approximate mathematical model of the coaxial pulsed plasma thruster [12 - 14].

2. CALCULATIONS OF THE MAIN PARAMETERS

The simulation results based on a developed mathematical model of coaxial magneto-plasma accelerator are shown in Figs. 1-5. These results correspond the following parameters of a helicon discharge: the working frequency of antenna is 13.56 MG, P_{hel} = 100 W, the working gas – *Ar*, P = 1 mTorr, R = 7.5 cm, L= 20 cm.

At the same time, geometrical and electrotechnique characteristics of CMPA have the following values: R_2 = 7.5 cm is the external radius and R_1 = 5 cm is the internal radius of the acceleration channel and inductor coils, L= 0.6 cm is the longitudinal length of inductor, the number of turns of the inductor is 2, U_0 = 5 kV, C_0 = 5 mF are the voltage and capacity of the capacitor bank, respectively.

Through the Fig. 1, we can see that the current J reaches its first maximum (J_1 = 7 kA) at the moment of t_1 = 3 μs and fades up to the minimum (t_2 = 9 μs) ahead in the electric circuit. The graphic dependence shows that the current is reversed in 6 s. Note, that the current drops to a value 7 kA, but the velocity is almost unchangeable parameter.

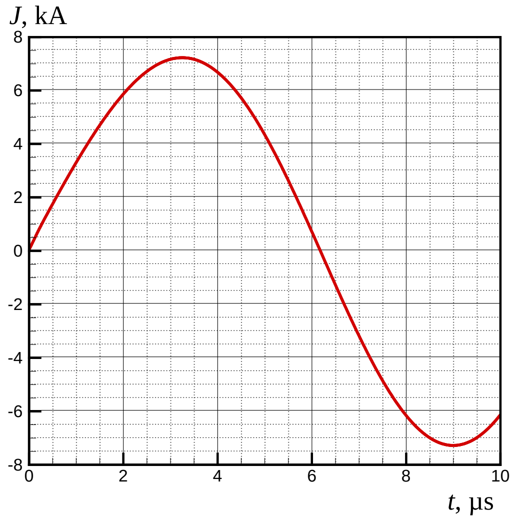

Fig. 1. Time dependence of the current J in the electric circuit of CMPA

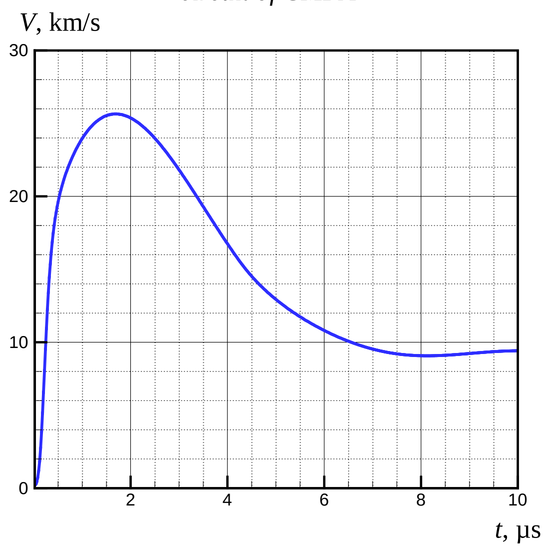

Fig. 2. The dependence of the plasmoid velocity V on the time t

Estimate using the formula from [15] shows that helicon waves excited in the plasma (for the range of parameters $10^{-3} \leq B_0 \leq 5 \cdot 10^{-3}$ T, P = 0.67 Pa, $T_e \approx 7$ eV) are weakly absorbed.

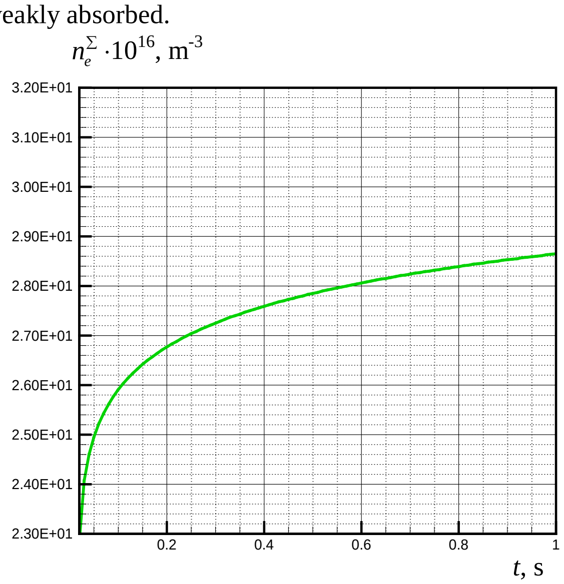

Fig. 3. The dependence of electron concentration n_e^{Σ} *on time t*

The Figs. 3-5 show that the most significant changes in thermophysical characteristics are observed at the initial stage ($t \leq 0{,}05$ s), i.e. power supply to the low-temperature rarefied plasma of the RF source.

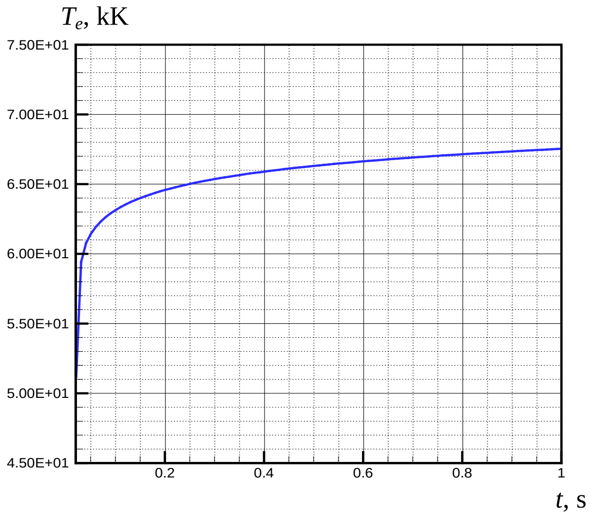

Fig. 4. The calculated electron temperature T_e *as a function of time t*

There is a strong temperature gap ($T_e \approx 70$ kK, and $T_i \approx 0.7$ kK) in the discharge plasma for the aforementioned characteristics of the RF discharge.

I.e. the energy (from an external power generator) supplied to the plasma accumulates basically in the internal energy of electrons and only partially changes the internal energy of ions.

Figs. 6, 7 show the dependence of the accelerating power and the dependence of the longitudinal coordinate upon the time, where the maximum growth in accelerating force occurs at times between 0 and 0.5 μs and spatial coordinates between 0 and 5 mm.

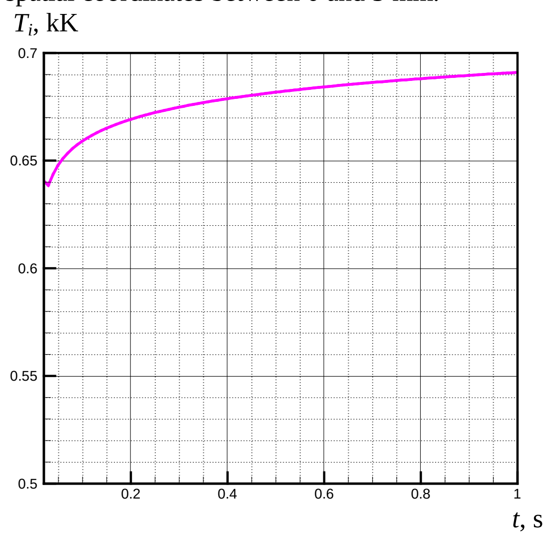

Fig. 5. Time evolution of ion temperature

Since the coordinate of the plasmoid is relatively small, then in this range of times increase in the speed is mainly caused by the interaction of the pulsed current of the inductor and the annular eddy current in the plasma, which gives rise to an electromagnetic force acting on plasmoid and provides its acceleration.

In the time range t > 0.5 μs the electrodynamic acceleration is mainly provided by the Ampere's force, e.g. by the interaction of magnetic field of electric

CMPA circuit with the current-carrying conductor (plasmoid). The accelerating force F_q (see Fig. 6) has the second extremum and quite prolonged (t > 2 μs) zone with negative value $F_q < 0$.

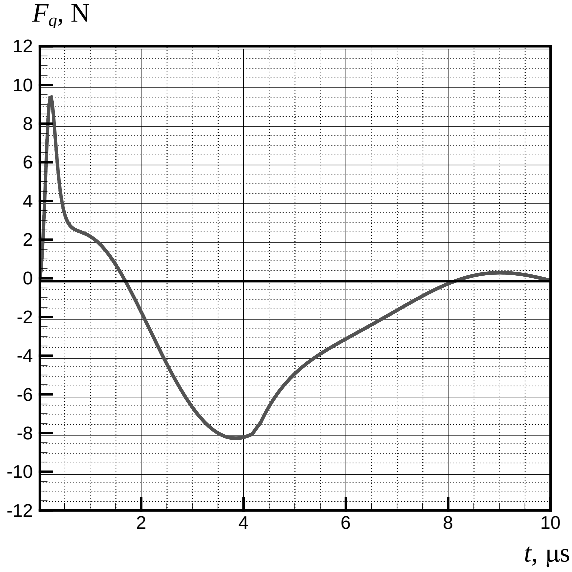

Fig. 6. The time dependence of the accelerating force acting on the plasmoid

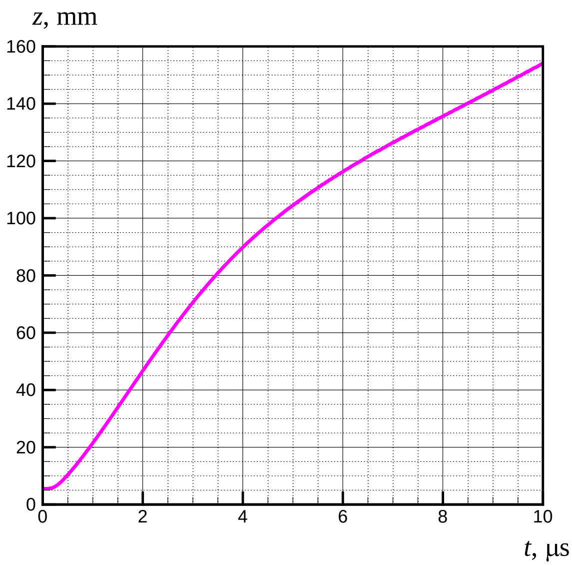

Fig. 7. The dependence of the longitudinal coordinate z of the plasmoid in the CMPA channel on time t

The calculations show that the most significant factor limiting the speed V and making a negative force F_q is the term $\left(dm/dt\right)dz/dt$, where m is the mass of the accelerated plasmoid. This term is responsible for the decrease in the acceleration by the plasma attachment over time, initially filling the accelerating channel of CMPA, and the evaporation of the electrode material [16 - 20].

Thus, it is clear from the above discussion that the acceleration channel length should be limited to the area where the accelerating force is positive, and the plasmoid velocity reaches the maximum value. Also note that the pulse flow of the working gas (axial or radial overlap) should be organized in a channel of the accelerator to speed up the plasmoid.

CONCLUSIONS

The approximate mathematical model was developed to get the main electrophysical characteristics of the coaxial magneto-plasma accelerator, including the preionization of the working substance by helicon discharge. This mathematical model takes into account shock waves in front of the plasma and its changing weight, gives a preliminary estimate of transformation of one type of energy to another, allows to estimate the contributions of different types of energy and to evaluate the mass of accelerated plasma.

It has been proposed to use a two-stage system to accelerate the plasma in CMPA. The first stage is constructed with inductor that forms a compact plasmoid and provides its initial acceleration and delivery to the accelerating channel of CMPA for a further acceleration (the second stage). The calculations that have been carried out demonstrate that the most essential factor (along with the braking force cause by appearing of a shock wave) which limits the value of plasma velocity is an attached mass which grows eventually.

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REFERENCES

1. A.K. Petrov, E.A. Kralkina. Study of Helicon Double Layer Thruster // *WDS'12 Proceedings of Contributed Papers*. 2012, Part II, p. 93-98.
2. S. Shinohara, T. Tanikawa, T. Hada, et al. High-Density Helicon Plasma Sources: Basics and Application to Electrodeless Electric Propulsion // *Fusion Science and Technology*. 2013, v. 63 (1T), p. 164-167.
3. E. Ahedo. Plasma dynamics in a helicon thruster / In L.T. DeLuca, C. Bonnal, O.J. Haidn, and S.M. Frolov, ed. // *Progress in Propulsion Physics*. 2013, v. IV of *EUCASS Advances in Aerospace Sciences*, chapter 3, p. 337-354.
4. F.F. Chen Ion ejection from a permanent-magnet mini-helicon thruster // *Physics of Plasmas*. 2014, v. 21, p. 093511.
5. A. Shabshelowitz, A.D. Gallimore, P.Y. Peterson. Performance of a helicon Hall thruster operating with Xenon, Argon, and Nitrogen // *Journal of Propulsion and Power*. 2014, v. 30, p. 664-671.
6. K. Takahashi, C. Charles, R. Boswell, and A. Ando. Performance improvement of a permanent magnet helicon plasma thruster // *J. Phys. D: Appl. Phys.* 2013, v. 46, p. 352001.
7. A. Cardinali, D. Melazzi, M. Manente, and D. Pavarin. Ray-tracing WKB analysis of Whistler waves in non-uniform magnetic fields applied to space thrusters // *Plasma Sources Sci. Technol.* 2014, v. 23, p. 015013.
8. S.V. Ryzhkov. The behavior of a magnetized plasma under the action of laser with high pulse energy // *Problems of Atomic Science and Technology*. 2010, № 4, p. 105-110.
9. V.V. Kuzenov, S.V. Ryzhkov. Numerical modeling of magnetized plasma compressed by the laser

beams and plasma jets // *Problems of Atomic Science and Technology*. 2013, № 1 (83), p. 12-14.
10. V.V. Kuzenov, S.V. Ryzhkov. Evaluation of hydrodynamic instabilities in inertial confinement fusion target in a magnetic field // *Problems of Atomic Science and Technology*. 2013, № 4 (86), p.103-107.
11. S.V. Ryzhkov. Current status, problems and prospects of thermonuclear facilities based on the magneto-inertial confinement of hot plasma // *Bulletin of the Russian Academy of Sciences. Physics*. 2014, v. 78, p. 456-461.
12. V.V. Kuzenov. *Fiziko-khimicheskaya kinetika v gazovoi dinamike*. 2014, v. 15, available at: http://chemphys.edu.ru/media/files/11-30-002- pdf (in Russian).
13. V.V. Kuzenov, S.V. Ryzhkov. Individual elements of the physical and mathematical model for a helicon discharge // *Applied Physics.* 2015, № 2, p. 37-44.
14. V.V. Kuzenov, P.A. Frolko. Approximated Model of the Coaxial Pulsed Plasma Thruster // *WCSE*. 2015.
15. Yu.P. Raizer. *Gas Discharge Physics*. Springer Verlag, Berlin, 1997, 449 p.
16. S.M. Mordyk, V.I. Voznyy, V.I. Miroshnichenko, et al. Helicon Ion Source in High Plasma Density Operation Mode // *Problems of Atomic Science and Technology*. 2006, № 5, p. 208-211.
17. V.F. Semenyuk, V.F. Virko, I.V. Korotash, et al. Controlling parameters determining technological properties of a helicon discharge system // *Problems of Atomic Science and Technology*. 2013, № 4, p. 179-182.
18. V.F. Virko, V.M. Slobodyan, K.P. Shamrai, et al. Helicon discharge excited by a planar antenna in a bounded volume // *Problems of Atomic Science and Technology*. 2014, № 6, p. 130-136.
19. I.A. Kotelnikov. On the density limit in the helicon plasma sources // *Physics of Plasmas*. 2014, v. 21, p. 122101.
20. S.V. Bobashev, B.G. Zhukov, R.O. Kurakin, et al. Intense shock waves and shock-compressed gas flows in the channels of rail accelerators // *Technical Physics*. 2015, v. 60 (1), p. 40-47.

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ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ ИМПУЛЬСНОГО ПЛАЗМЕННОГО ДВИГАТЕЛЯ С СИСТЕМОЙ ПРЕДИОНИЗАЦИИ НА ОСНОВЕ ГЕЛИКОННОГО РАЗРЯДА

В.В. Кузенов, Т.Н. Полозова, С.В. Рыжков

На основе разработанной приближенной математической модели импульсного плазменного двигателя и системы предионизации рабочего газа с геликонным разрядом проведен расчет основных электрофизических характеристик коаксиального импульсного магнитоплазменного ускорителя с емкостным источником питания. Представлены основные параметры ВЧ-источника и зависимости теплофизических характеристик аргоновой плазмы от времени.

ЧИСЕЛЬНЕ МОДЕЛЮВАННЯ ІМПУЛЬСНОГО ПЛАЗМОВОГО ДВИГУНА З СИСТЕМОЮ ПРЕДІОНІЗАЦІЇ НА ОСНОВІ ГЕЛІКОННОГО РОЗРЯДУ

В.В. Кузенов, Т.Н. Полозова, С.В. Рижков

На основі розробленої наближеною математичної моделі імпульсного плазмового двигуна і системи передіонізації робочого газу з геліконним розрядом проведено розрахунок основних електрофізичних характеристик коаксіального імпульсного магнітоплазмового прискорювача з ємнісним джерелом живлення. Представлено основні параметри ВЧ-джерела і залежності теплофізичних характеристик аргонової плазми від часу.