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# Plasma Source Based on Helicon Discharge for a Plasma Accelerator

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**Abstract.** Several assumptions for simplifying the mathematical description of the accelerating channel of coaxial magneto-plasma accelerator are presented. A closed approximate mathematical model allows to calculate the basic electrophysical characteristics of the pulsed coaxial magneto-plasma accelerator with the capacitive power supply and the working gas preionization system on the basis of the Helicon discharge. The initial verification of numerical calculation results made based on an approximate quasi-one-dimensional mathematical model of the RF inductive plasma source and the experimental data is produced.

## INTRODUCTION

The electrodeless plasma thruster based on a helicon discharge is called a helicon engine. These thrusters use different propellants and can be applied as the main, correction, orientation and stabilization engines for geostationary or low-orbit spacecrafts (microsatellites) [1-4]. Helicon thrusters are also developed to study the processes of interaction of plasma with matter in open magnetic systems and other applications [5-14].

The accelerating channel of the coaxial magneto-plasma accelerator (CMPA) is similar to the tube-in-tube heat exchanger. A spatial domain is located between two tubes with different diameters (cylindrical and central electrodes) which are located coaxially one in another.

Cylindrical electrode with a constant cross section has a diameter bigger than the diameter of the central electrode located on the axis of symmetry of CMPA. Besides, the solenoid (inductor) is a part of the accelerator construction and consists of the system of coils with a circular cross section.

In general way the mathematical description of the system of CMPA-accelerated plasmoid can be obtained on the basis of the equations of an electric contour, the three-dimensional non-stationary equations of magnetic hydrodynamics, Maxwell's equations with equations of state of the plasma. The solution of such problem is connected with sufficient mathematical and calculative difficulties, demands a lot of time for the program development and many computational resources. That's why phenomenology that is happened in CMPA is effectual to lead to calculation of transition processes in an electro technical equivalent circuit.

The assumption which is taken as the basis for an equivalent circuit creation is that conductivity of the accelerated plasmoid material is infinite ( $\sigma = \infty$ ). Such approach is justified if the depth of the magnetic field diffusive penetration  $\delta_g(t)$  into the plasma of the accelerated clot is less, than the thickness  $\delta$  of the area occupied by plasma at the stage of its effective acceleration, and the level of Joule losses in the accelerated plasma is much less, than its kinetic energy. The value of the ohmic losses of the energy in the accelerated plasma isn't usually sufficient and in the modes they doesn't exceed 3÷5% of the initial energy of the capacitor power supply.

The second assumption of the CMPA model is applied when a magnetic field is calculated near of a geometry inductor task which is presented in the form of the concentric rings system. Each of them has the identical current  $J(t)$ , that is concentrated in the geometrical center of a coil cross section (we neglect the spatial distribution of the current density in the coil cross section).

The closed approximate mathematical model which allows to calculate the main electrophysical characteristics of the coaxial flash magnetoplasma accelerator with the capacitor power supply and the working gas preionization system on the basis of the helicon discharge developed in [15, 16].

## SOME PHYSICAL CHARACTERISTICS CALCULATIONS OF THE LOW-TEMPERATURE RAREFIED PLASMA RF-SOURCES

The models developed by author allow carrying out calculations of thermophysical parameters, electric and magnetic of a cylindrical plasma source excited by the current antenna located on an approach surface of the cylinder. It should be confirmed by the comparison of numerical results with the known analytical solutions or with the published numerical and experimental results.

In this section, the initial verification of numerical results data is made. These results were executed on the basis of the approximate quasi-one-dimensional mathematical model of an inductive plasma RF-source.

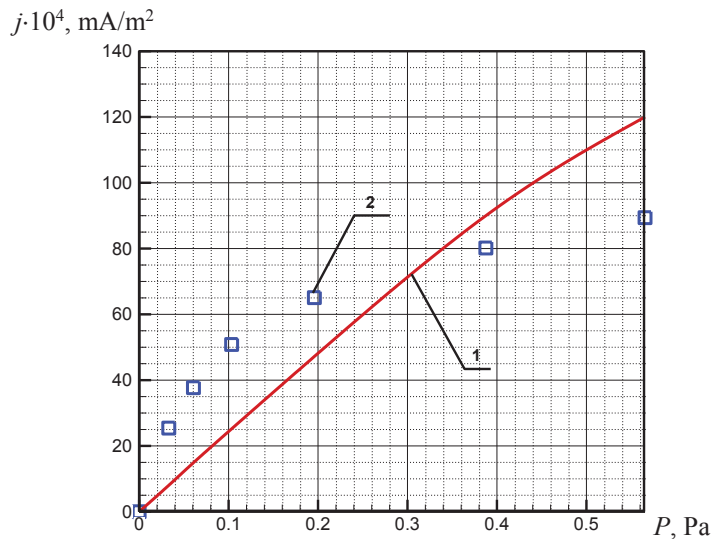
The first verification group uses mathematical model that is developed in this work. This model describes mechanisms of the RF power absorption by plasma and considers energy losses that are brought to plasma from an external electric chain.

The second verification group is based on the mathematical model, which establishes mathematical connection between the power contribution  $P_{hel}$  of the helicon and plasma parameters of the ions RF-source.

The RF discharge characteristics observed in the experiments usually located in the following intervals:

- The size of the computational domain are  $R \approx 0.02 - 0.1$  m,  $L \approx 0.05 - 0.15$  m;
- Concentration  $n_e^\Sigma = 10^{16} - 10^{19}$  m<sup>-3</sup> and electron temperature  $T_e = (3-9) \cdot 10^4$  K;
- The external magnetic field is  $B = 0.001 - 0.04$  T;
- The pressure of the working gas is  $p = 0.01 - 10$  Pa.

The executed calculations have shown that this physical values corresponds to the calculated values within an experimental error.

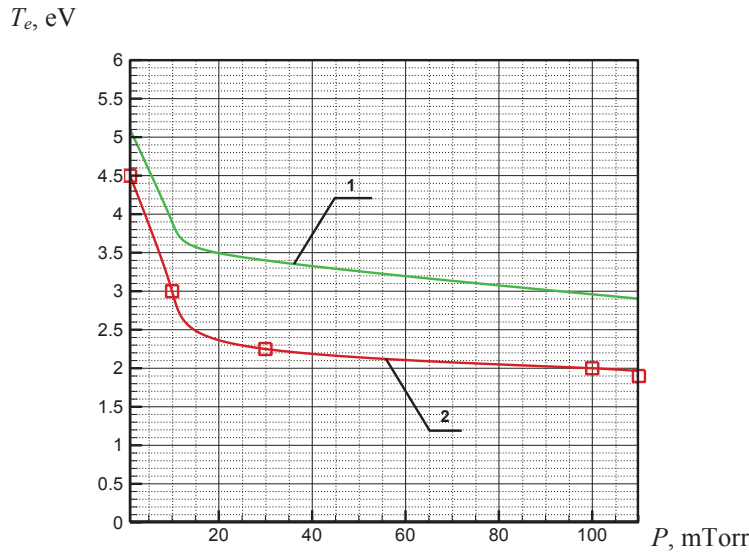


**FIGURE 1.** The calculated (1) and experimental (2) current density as a function of argon plasma pressure. The antenna frequency is 13.56 MHz,  $P_{hel} = 800$  W,  $B = 0.012$  T,  $R = 0.1$  m,  $L = 0.25$  m

The experimental device belonging to the first verification group is described in [17] and consists of the 0.2 m diameter and 0.25 m length quartz reactor. The helicon antenna is set around this reactor and is connected to the generator of high frequency through the coordinating device.

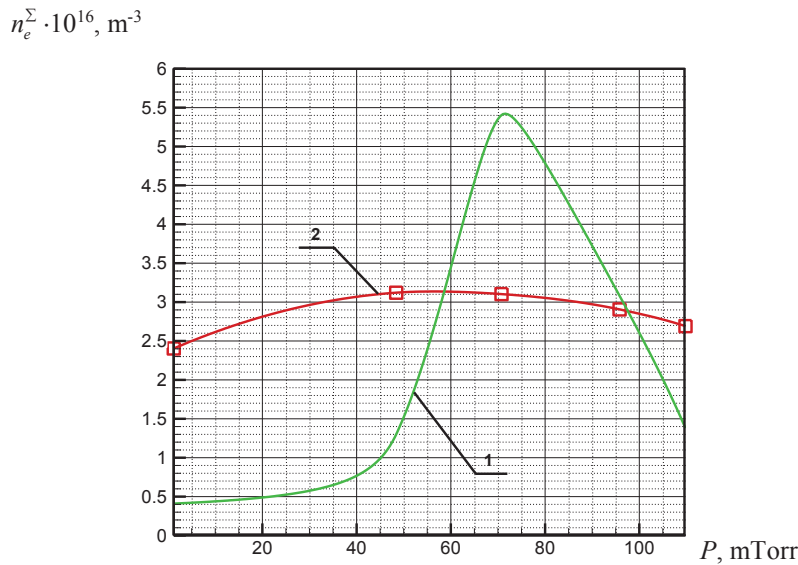
The metal nonmagnetic screen on which the electromagnets are set, creating an adjustable magnetic field in the reactor, closes the reactor. The comparison results are shown in Fig. 1 (the experimental results error is 10-15%). The probe measurements that were implemented in this work in various operating modes of a source have shown that the electron concentration in plasma reached  $n_e^\Sigma = 10^{19}$  m<sup>-3</sup>, and the energy of electrons is  $T_e = 3-5$  eV. At the

same time in the calculations performed on the developed mathematical model, the concentration of electrons is close to  $n_e^\Sigma = 0.4 \cdot 10^{19} \text{ m}^{-3}$ , and the temperature of electrons is  $T_e = 4.5\text{-}5.9 \text{ eV}$ .



**FIGURE 2.** Calculated (1) and experimental (2) electron temperature depending on plasma pressure

The electron temperature depending on the pressure of working gas in RF-inductive plasma source without external magnetic field is shown in Fig. 2. One of these calculated correlations (the curve 1) is received on the basis of the mathematical model that is developed by author, and the second calculated correlation (the curve 2) is taken from [18]. These results correspond the following parameters of a helicon discharge the carrier frequency of the antenna is 13.56 MHz,  $P_{hel} = 800 \text{ W}$ , the working gas is Ar,  $B = 0.012 \text{ T}$ ,  $R = 23 \text{ cm}$ ,  $L = 30 \text{ cm}$ .



**FIGURE 3.** Calculated (1) and experimental (2) electron density depending on gas pressure

At the same time the curve 2 is obtained on the basis of the mathematical model [18] for RF-inductive argon plasma source with a diameter  $D = 0.46 \text{ m}$  and length  $L = 0.3 \text{ m}$  in the range of pressure  $P \approx 1\text{-}100 \text{ mT}$ . The electron concentration depending on the pressure of the working gas in the RF-inductive plasma source is represented by the Fig. 3. The curve 1 is obtained in this work, and the curve 2 corresponds to paper [18]. The experimental device [19] related to the first verification group and is capable to work in the mode with the issue

current density  $j \approx 10^4\text{-}10^6$  mA/m<sup>2</sup> and the power invested into plasma  $P_{hel} \leq 350$  W. It consists of the helicon RF ion source with the compact magnetic system with permanent magnets and tread-band mould - ferrites, the ion-optical system in which the cathode is separated from plasma by a quartz disk with a hole, and is positioned out aperture of a source.

## SUMMARY

The presented mathematical model allows users to calculate thermophysical parameters, electric and magnetic RF fields in a cylindrical plasma source excited by a current of the loop antenna located on the side surface of the plasma cylinder. In comparison with the general case the mathematical description of the CMPA system (based on the solution of electric circuit equations, the three-dimensional nonstationary equations of magnetic hydrodynamics and Maxwell equations, accounting the relevant thermodynamic equations of state) significantly simplifies the computational process. Results of the verification confirm the correctness of the selected models.

## ACKNOWLEDGMENTS

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