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To cite this article: V V Kuzenov *et al* 2017 *J. Phys.: Conf. Ser.* **830** 012049

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Numerical simulation of the coaxial magneto-plasma accelerator and non-axisymmetric radio frequency discharge

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Abstract. The paper presents the results of mathematical modeling of physical processes in electronic devices such as helicon discharge and coaxial pulsed plasma thruster. A mathematical model of coaxial magneto-plasma accelerator (with a preionization helicon discharge), which allows estimating the transformation of one form of energy to another, as well as to evaluate the level of the contribution of different types of energy, the increase in mass of the accelerated plasmoid in the process of changing the speed. Main plasma parameters with experimental data were compared.

1. Introduction

The theoretical work presented in this contribution applies a radio-frequency (RF) wave-heated (helicon) plasma as an alternative concept for ion sources in various applications [1–7]. An approximate mathematical model of a helicon type plasma source (coaxial pulsed plasma thruster) was developed and calculation based on the developed multiparameter computational model was previously done.

The approximated mathematical model of radio-frequency ion source of helicon-type plasma and coaxial multi-plasma accelerator was created in [9–12]. Such devices can be used for high temperature plasma applications involving materials science. The initial verification of computing results on the basis of a group of experimental data was done. These computations were made with the use of self-approved approximated mathematical model of RF plasma source. The estimate of various power types contributions into the process of acceleration and transformation of one type of energy into the other was performed. Analyzed RF devices can be used as the plasma sources to solve problems in materials science [13].



The aim of this work is to compute main electrophysical characteristics of a coaxial magneto-plasma accelerator with the voluminous energy source. The coaxial magneto-plasma accelerator (CMPA) with a preionization helicon discharge [8–12] is considered.

2. Calculation of the main characteristics of RF ion source

The RF source extraction system has the following sizes: the length of the cathode channel $l = 3$ mm, the diameter of the channel $d = 0.6$ mm. The gas discharge bulb is made of quartz and has the outer diameter of 0.03 m and length of 0.2 m.

RF power system consists of a main oscillator with an operating frequency $f = 27.12$ MHz, the power amplifier "Acom-1000" and matching unit, providing power up to 400 W in continuous mode [14]. The sources used a spiral antenna that contains 4 coils of copper wire with a diameter of 4 mm.

Computational and theoretical modeling is performed based on the developed numerical method. The experiment has been conducted using an ion beam accelerating device [14], which is suitable for injectors and other applications. Figures 1–4 present theoretical and experimental curves for the following discharge parameters: antenna frequency $f = 27.12$ MHz, magnetic field $B = 3 \cdot 10^{-2}$ T, gas pressure $p = 1.33$ Pa, antenna radius $R = 0.015$ m, and antenna length $L = 0.13$ m. The electron density n_e^Σ and ion current density j versus the RF power P_{hel} for discharge in helium are given in Figures 1 and 2. The electron density n_e^Σ as a function of RF power P_{hel} in argon discharge is presented in Figure 3, and the power W_{hel} embedded in RF plasma ion source with hydrogen plasma is shown in Figure 4 for Ar.

In Figures 1 and 3 we have plotted the change in electron density n_e^Σ versus power P_{hel} , supplied to the helicon antenna. Curve 1 is obtained from the mathematical model described in this work, while the experimental curve 2 is taken from Ref. 14.

The ion current density j increases with the RF power P_{hel} as shown in Figure 2: the calculated values (curve 1) and experimental results (curve 2). When comparing experimental data with the theoretical values, the mathematical model developed by the authors is used.

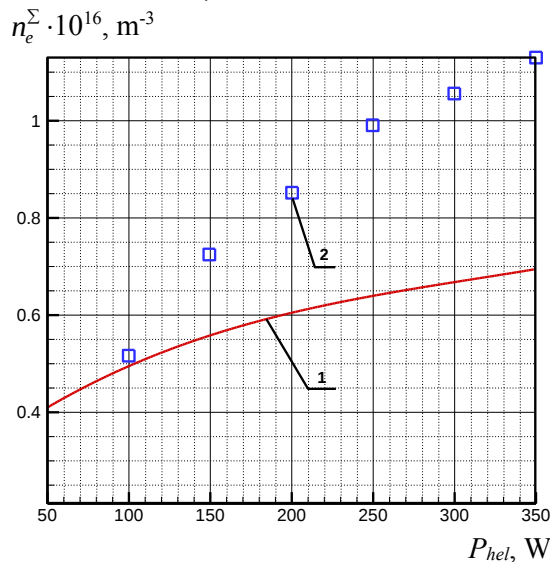


Figure 1. The variation of the electron density n_e^Σ on the RF power P_{hel} for He discharge: 1) calculation, 2) experiment.

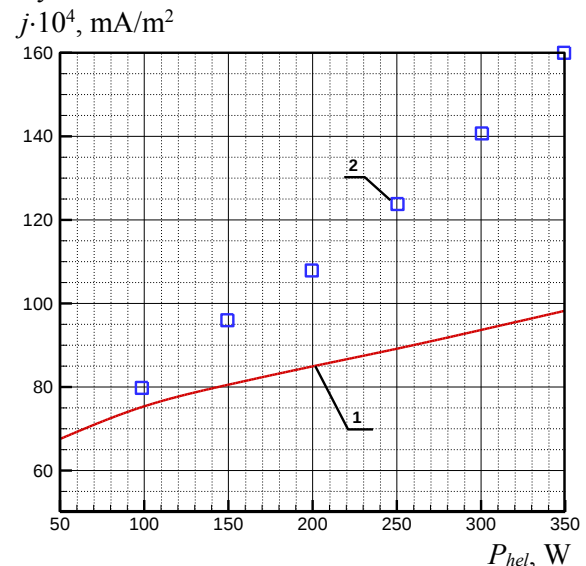


Figure 2. Comparison of calculated (1) and experimental (2) dependences of the ion current density j on helicon power P_{hel} in He as working gas.

The power W_{hel} embedded in the RF plasma source versus the electron density n_e^Σ is shown in Figure 4. The experimental and calculated dependencies of practically important characteristics, as the ion current density j (Figure 2) and the electron density in the RF source (Figure 3), show that the error lies in the range of 15–20% for power $P_{hel} \leq 150$ W, injected into plasma.

When the power level is imbedded in the discharge plasma $P_{hel} > 200$ W, there is a maximum in error value $>35\%$. However, in this case, the ion current density j is strongly depending on the electrical parameters of the extraction system which is not taken into account in the mathematical modeling.

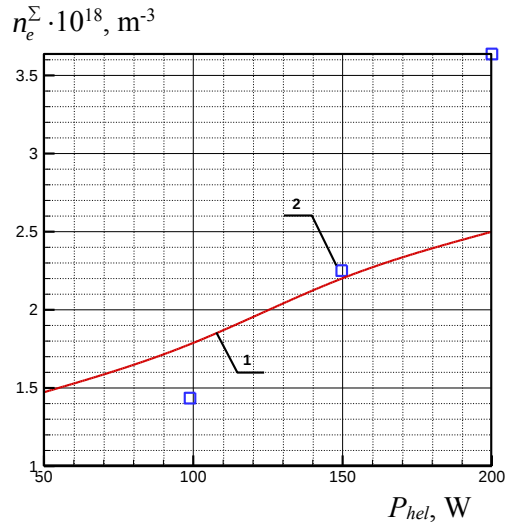


Figure 3. The calculated (1) and experimental (2) electron density n_e^Σ as a function of RF power P_{hel} in Ar discharge.

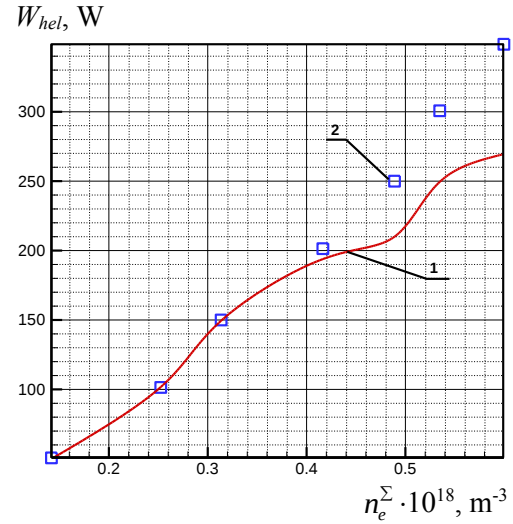


Figure 4. Comparison of calculated (1) and experimental (2) dependencies of the power W_{hel} , embedded in RF plasma ion source in H as working gas.

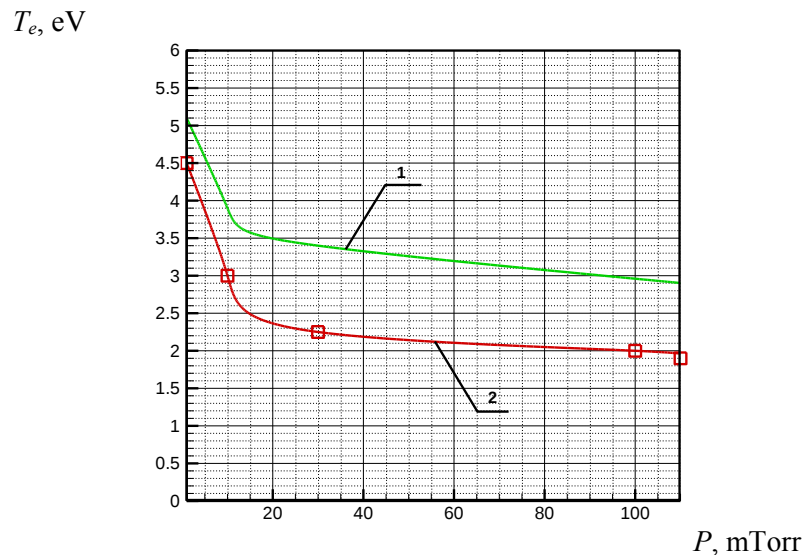


Figure 5. Comparison of 1) calculation with 2) experimental data on electron temperature T_e vs. Ar pressure P . $f = 13.56$ MHz, $P_{hel} = 0.8$ kW, $B = 1.2 \cdot 10^{-2}$ T, $R = 0.23$ m, $L = 0.3$ m.

Let us consider the following results of power W_{hel} in the RF ion source: experimental and calculated data (Figure 4) agree satisfactory. Figure 5 shows the pressure P dependence of the electron temperature T_e and one can see that the behavior of the curve 1 is qualitatively similar to that of curve 2. At the same time, it is difficult to judge quantitatively because the verification of calculations is not presented in [15].

In general, the comparison gives that the precision of the calculation we have carried out for ion current density j depends on the accuracy of mathematical model describing the process of ion extraction from the end surface of a RF source, especially at $P_{hel} > 200$ W. Increase of calculation accuracy of the energy fraction lost by radiation, ionization and recombination processes may increase the accuracy of the determination of electron density n_e^Σ and temperature T_e .

At the same time, it is clear that the most precise and accurate results can be received by considering the inductive and helicon discharge as non-linear, self-consistent physical system.

Therefore, joining of computer codes of two basic elements of a mathematical model into one code, which allows us to solve the self-consistent problem (to perform an initial assessment) for the calculation of RF electric and magnetic fields in a cylindrical plasma source, is performed for finding the excitation conditions and the analysis of wave absorption mechanism in specific models of plasma source. RF fields were excited by antenna located on the side surface of the plasma cylinder.

Calculations carried out taking into account the thickness of collision δ_c and collisionless δ_a skin layer under experimental conditions [16] shows that the specified values are $\delta_c \approx 0.09$ m and $\delta_a \approx 0.02$ m. This difference between collision thickness and anomalous skin depth allows speaking about a possible non-uniformity of the radial distribution of the electron density n_e^Σ .

Calculated dependence of density, electron and ion temperature in argon plasma on time are given in Figures 6–8 with the following values of electrotechnical and geometrical characteristics of RF source: $P_{hel} = 0.1$ kW, $B_0 = 0.28 \cdot 10^{-2}$ T, $R = 0.075$ m, $L = 0.2$ m. Systems operate at 13.56 MHz.

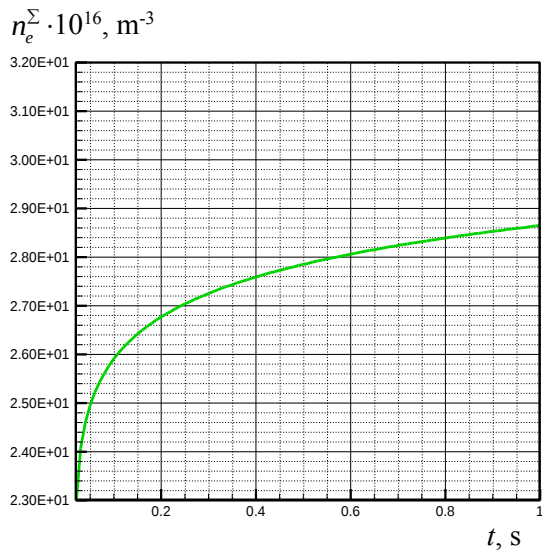


Figure 6. The time dependence of plasma electron density.

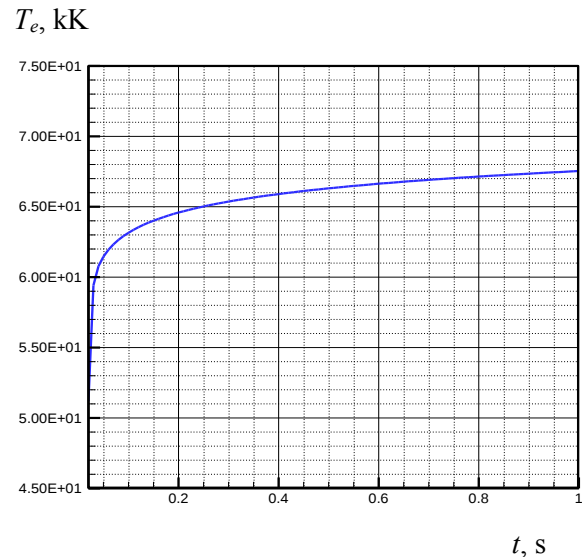


Figure 7. The calculated dependence of electron temperature T_e on time.

An evaluation by the formula from [17] shows in this case ($10^{-3} \geq B_0 \leq 5 \cdot 10^{-3}$ T, $P = 0.67$ Pa, $T_e \approx 7$ eV) that helicon waves excited in plasma are poorly absorbed.

Figures 6–8 show that the most significant changes in heat characteristics are observed at the initial stage ($t \leq 0.05$ s) of energy supply to the low-temperature rarefied plasma source.

In the plasma for the above values of electrical and geometrical characteristics of the RF discharge, a strong discontinuity is observed in the ion T_i and electron T_e temperature: $T_e \approx 70$ kK, and

$T_i \approx 0.7$ kK, i.e. the energy supplied to plasma from an external power generator is mainly accumulated in the internal energy of the electrons and only partially changes the internal energy of ions.

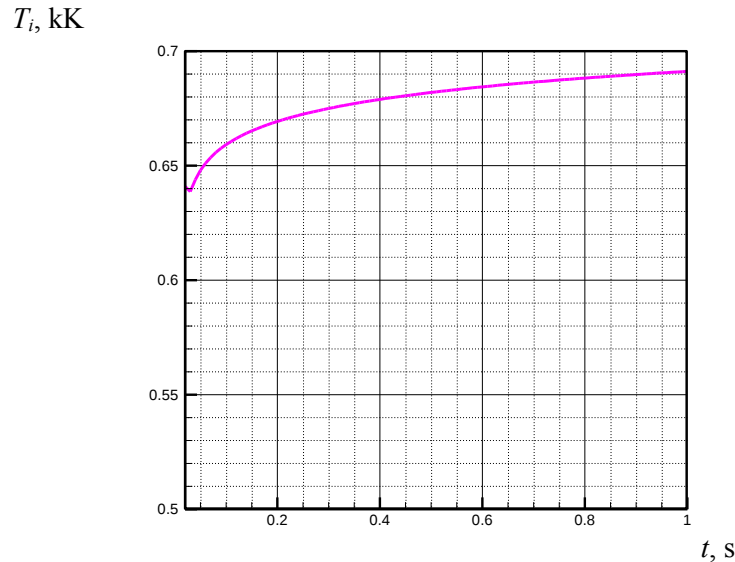


Figure 8. The time dependence of ion temperature.

3. Conclusion

The simplified kinetic scheme, developed by authors, was used to calculate the component composition of molecular hydrogen plasma in the helicon discharge chamber. The kinetic scheme includes the processes of ionization of molecules and hydrogen atoms by electron impact recombination processes, various mechanisms dissociation of hydrogen molecules by electron impact. The results of numerical modeling of the kinetics of ionization and dissociation of molecular hydrogen in a partially ionized plasma, helicon discharge are presented.

The calculations revealed that the most significant factor (along with the formation of a shock wave), limiting the amount of plasmoid velocity in the CMPA channel, is attached mass increasing over time.

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Acknowledgments

This work was supported by the Russian Science Foundation (Project No. 16-11-10275).