St. Petersburg Polytechnic University Journal. Physics and Mathematics. 2023. Vol. 16. No. 3.1
Научно-технические ведомости СПбГПУ. Физико-математические науки. 16 (3.1) 2023

Conference materials
UDC 53.09
DOI: https://doi.org/10.18721/JPM.163.135

Formation features of motion trajectory of mercury-199 ions in the quantum frequency standard for space applications

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Abstract. The necessity of developing an atomic clock that can operate without adjusting the scale during a satellite-to-Earth communication session is substantiated. This is necessary to place a satellite constellation in higher orbits, where a stable and long communication session with the Earth cannot always be realized. It is also necessary during a long flight in outer space (between planets). The problems that arise in the operation of the current models of atomic clocks now in use in orbit are mentioned. It has been established that the most promising solution to this problem is the use of atomic clocks on mercury-199 ions. The main problem that arises when reducing the size of the structure of atomic clocks on mercury-199 ions when they are placed on a satellite or on an autonomous space mobile object is considered in detail. To solve this problem, a mathematical model has been developed to calculate the trajectory of mercury-199 ions in the Paul trap when its dimensions change, which must be selected in accordance with the technical characteristics of the satellite or moving object. The modeling results of ion motion trajectory depending on the parameters of trap rods and control voltages are presented. Options for determining the optimal parameters of ion trap under conditions of limited volume and mass of the atomic clock are proposed.

Keywords: Global navigation satellite systems, quantum frequency standard on mercury-199 ions, Paul trap, Mathieu equation, trajectory of ions, optimal parameter

Citation: Wang D., Davydov V.V., Formation features of motion trajectory of mercury-199 ions in the quantum frequency standard for space applications, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 16 (3.1) (2023) 198–203. DOI: https://doi.org/10.18721/JPM.163.135

Материалы конференции
УДК 53.09
DOI: https://doi.org/10.18721/JPM.163.135

Особенности формирования траектории движения ионов ртути-199 в квантовом стандарте частоты космического применения

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Аннотация. Обоснована необходимость разработки атомных часов, которые могут работать без корректировки шкалы во время сеанса связи спутника с Землей. Это необходимо для размещения спутниковой группировки на более высоких орбитах, где устойчивый и продолжительный сеанс связи с Землей можно реализовать не всегда. Также это необходимо во время длительного полета в открытом космосе (между планетами). Отмечены проблемы, которые возникают при эксплуатации действующих моделей атомных часов, которые применяются сейчас на орбите. Установлены, что наиболее перспективным решением данной задачи является использование атомных часов на ионах ртути-199. Подробно рассмотрена основная проблема, возникающая при уменьшении размеров конструкции атомных часов на ионах ртути-199 при размещении их на спутнике или на автономном космическом подвижном объекте. Для решение этой проблемы разработана математическая модель для расчета траектории движения ионов ртути-199 в ловушке Пауля при изменении ее размеров, которые необходимо подбирать в соответствии с техническими характеристиками спутника или подвижного объекта. Представлены результаты моделирования траектории движения ионов в зависимости от параметров стержней ловушки и управляющих напряжений. Предложены варианты определения оптимальных параметров ионной ловушки в условиях ограничения объема и массы атомных часов.

Ключевые слова: глобальные навигационные спутниковые системы, квантовый стандарт частоты на ионах ртути-199, ловушка Пауля, уравнение Матье, траектория движения ионов, оптимальный параметр

Ссылка при цитировании: Ван Д., Давыдов В.В. Особенности формирования траектории движения ионов ртути-199 в квантовом стандарте частоты космического применения // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2023. Т. 16. № 3.1. С. 198–203. DOI: https://doi.org/10.18721/JPM.163.135

Introduction

Time is one of the seven fundamental physical quantities. Any failure in the system can make our lives disorganized. It is extremely important to determine time with high accuracy in communication systems, satellite navigation systems, parallel computing, and other related applications [1–4]. Satellite navigation systems rely on quantum frequency standards or atomic clocks to determine the location of an object on Earth [5–11]. These devices have a low power consumption, which is important for autonomous operation of all systems powered by solar panels through batteries [12–15].

In this situation, the quantum frequency standard on mercury-199 ions may be the best option [16, 17]. The experimental data has shown that without adjustment of atomic clocks during communication sessions with Earth, the frequency stability of the quantum frequency standard on mercury-199 ions did not deteriorate below 10^{-13} [17] for five years of flight in space. It should be noted that the stability of one day has reached the same level as the active maser (10^{-15}) [17–19]. In the current designs of frequency standards on ^{87}Rb and ^{133}Cs atoms in space orbit, it is necessary to adjust the standard scale in the time interval from 6 to 24 hours [20]. For the standard with the active maser the maximum time of stable operation without adjusting the scale is 48 hours. Failures in the operation of these standards are associated with magnetic storms in space, frequency shifts, collisions with vessel walls, etc. [6, 20]. The quantum frequency standard on mercury-199 ions is devoid of these shortcomings [6, 10, 16–19].

The principle of operation of the quantum frequency standard on mercury-199 ions has been mentioned in several articles [6, 10, 16–19], and it is worth noting that one of the main elements is the Paul trap, whose size is related to the size of the quantum frequency standard on mercury-199 ions. It should be noted that a large number of designs of Paul traps have been developed for laboratory studies and prototypes of ground-based frequency standards [6, 21, 22] using various ions. All of these options are not suitable for space applications due to the poor resistance of these ions and optical pumping systems to radiation during long-term exposure. Furthermore, high power consumption compared to the quantum frequency standard on mercury-199 ions. It is also worth noting that manufacturing a new design of the Paul trap is necessary for each configuration of a satellite or a moving object for deep space exploration. In this trap, it is necessary to ensure the maximum inversion of mercury-199 ions in order to obtain the maximum signal-to-noise ratio, which ensures a frequency stability of at least 10^{-13} during long-term operation. This depends on the stable placement of ions in a given zone of the Paul trap, taking into account its design.

Therefore, in this work, we considered the motion of ions in an ion trap under the conditions of volume and mass constraints of atomic clocks.

Motion equation for mercury-199 ions and simulation process

The studies performed have shown that using the following design is most expedient for reducing the size of the Paul trap in the quantum frequency standard on mercury-199 ions. In this design, there are four parallel rods, wherein two adjacent rods have identical potentials but opposite electrodes. Ions are introduced into the Paul trap with a certain initial velocity and are trapped inside. The ion motion equation is described by the Mathieu equation, the mathematical expression of which is presented in formula (1) for the x direction:

$$\frac{d^2x}{d\tau^2} + (a_x - 2q_x \cos 2\tau)x = 0, \quad (1)$$

where $\tau = \frac{\omega t}{2}, a_x = \frac{8eU}{mr_0^2\omega^2}, q_x = \frac{4eV}{mr_0^2\omega^2}$, t – time, e – electrical charge, m – mass of mercury-199 ions, ω – angular frequency, a_x and q_x – Mathieu parameters, r_0 – Radius of the inscribed circle, U – DC Voltage, V – AC Voltage. The solutions of this equation are divided into stability solutions and instability solutions, which depends on the values of a_x and q_x. In the case of determining the trap model, a_x is only related to the DC voltage, q_x is only related to the AC voltage. The first stability zone is usually studied, which is formed by the intersection area of the x-direction stability zone (trajectory along the x-direction) and the y-direction stability zone [6].

To study the trajectory of motion of mercury-199 ions, we used the software Comsol. For this purpose, we used the Electrostatics (es), Electric Currents (ec) and Charged Particle Tracing (cpt) modules in Comsol, the first two modules to calculate electric fields of DC and AC, and the third module to simulate the trajectory of ion motion. It requires data from the first two modules as support. This is a new model for studying the trajectory of mercury-199 ions (it has no analogues). Fig. 1 shows our complete simulation process.

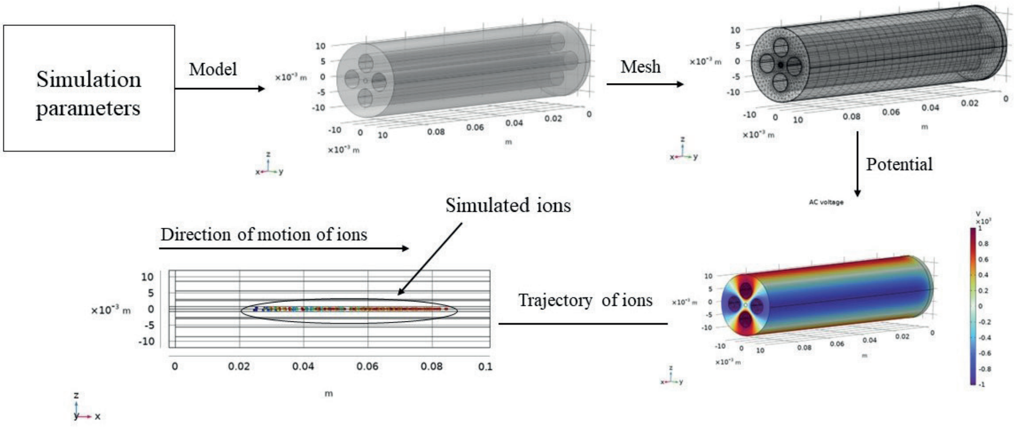

Fig. 1. Simulation process

Based on the simulation parameters and the mathematical equation of ions motion (1), we built a three-dimensional model of the ion trap in the software Comsol. A feature of the model developed by us is the need to set the parameters L and r_s for calculating the trajectory. There are no restrictions on the values of these parameters (this makes the developed model universal). Fig. 1 is an example of a case for length L = 100 mm, rod radius r_s = 3 mm. For these values L and r_s is added simulation conditions and adjusted the Mathieu parameters a и q. After completing the settings, we launched the software Comsol and after waiting we obtained the potentials of the ion trap and the trajectory of ions in the ion trap.

Next, we fixed the remaining parameters and simultaneously changed the values of the Mathieu parameters, repeated the simulation process described above and observed all the simulation results.

Results and Discussion

Based on the results of all our simulations in the software Comsol, we redrew the graph of the relationship between the Mathieu parameters a and q in the first stability zone, which is shown in Fig. 2.

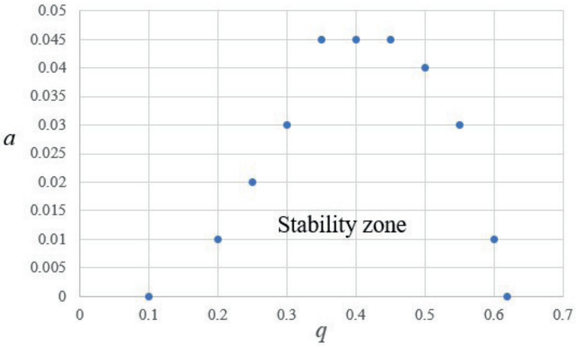

Fig. 2. Simulation results of the Mathieu parameters a and q

From Fig. 2, it can be seen that the stability zone of ion motion is below the region covered by dots, and outside the region covered by dots is the instability zone.

To verify the correctness of the simulation results, we selected several sets of three points (inside the stability zone, at the boundary of the stability zone, and outside the stability zone) in Fig. 2 with the same values of q and different values of a, and checked them several times. Fig. 3 shows the results of our verification simulation at q = 0.45, a = 0.03, 0.045, and 0.05.

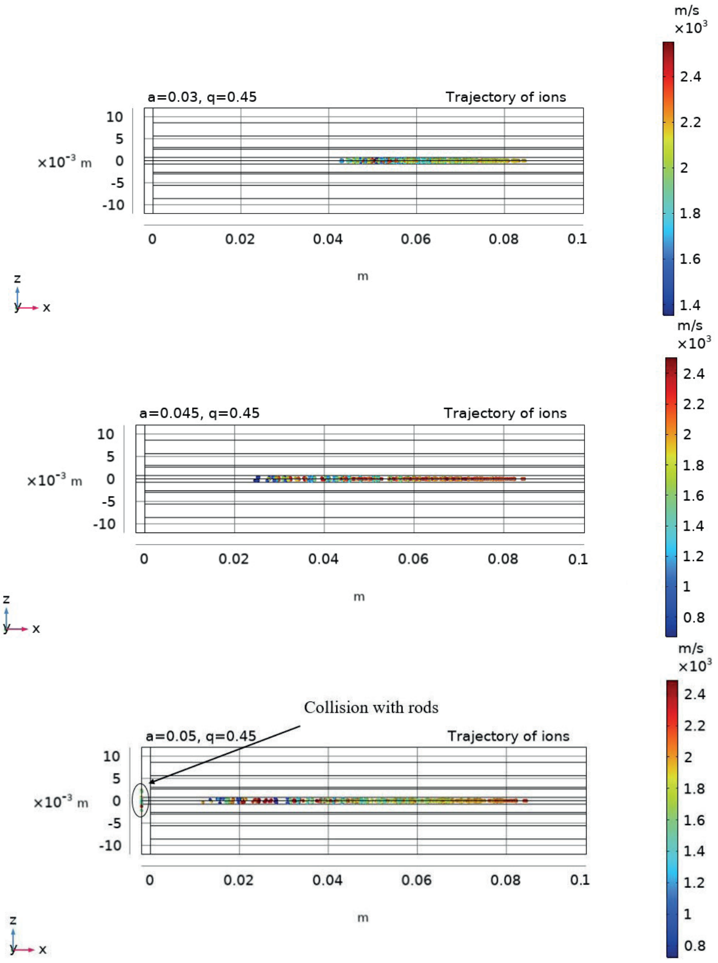

Fig. 3. Simulation results for different conditions with q = 0.45 (The first one is within the stability zone, the second one is at the boundary, and the third one is outside stability zone)

From Fig. 2 it can be seen that when $a = 0.03$, $q = 0.45$ is in the stability zone, $a = 0.045$, $q = 0.45$ is at the boundary, it is optimal parameter, ions under these conditions did not collide with rods; when $a = 0.05$, $q = 0.45$ is in the instability zone, so ions collided with rods, which corresponds to Fig. 3. It can be assumed that the simulation results are correct.

Conclusion

The analysis of the obtained results shows that optimizing the parameters of the rods and choosing their configuration for a particular trap design is a key task for designers. Limitations on the size and weight of the trap create problems in calculating its parameters and using new materials with various additions for its production. It has been established that solutions to this complex problem can be obtained using the model developed by us based on the Mathieu equation (the coefficients used in the equations depend on the material of rods, which can be established by experimental studies and further applied in our model).

Acknowledgments

This thesis was supported by the China Scholarship Council.

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Received 09.07.2023. Approved after reviewing 01.09.2023. Accepted 02.09.2023.