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Electron-Ion Trap for Combined Density and Composition Sensor of the Upper Atmosphere

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[1]V.E. Dreyzin., [2] Al Kadhimi Ali Noori Mohammed, [3]Ahmed Raisan Hussein

[1]*Dr. Techn. Sciences, Professor. of SOUTHWEST State University.   Department of Electronics, radio engineering and communication system. SOUTHWEST State University. (E-mail: drejzin-ve@yandex.ru). +79103148445, ,305016, Kursk, street Pavlovskogo, 1, ap.93. Kursk /Russia.*

[2]*post-graduate student, SOUTHWEST State University», Department of Electronics, radio engineering and communication system. SOUTHWEST State University.*
 (E-mail:alinoorimm@yahoo.com). +79051540006, 305040, 50 Let Oktyabrya Street, 94. Kursk/Russia.

[(2)] *(E-mail: alinoorimm@yahoo.com). +9647801620595 Ministry of Oil, Baghdad Oil Training Institute (BOTI), ALwazirya behind the Ministry of work. Baghdad /Iraq.*

[3]*Dr. Head of electrical engineering Departement/ college of engineering /Misan university. (E-mail: Alhusseinahmed70@uomisan.edu.iq). +9647708861738. Misan/Iraq.*

Abstract. The urgency and problems of instrumental studies of the density and composition of the upper atmosphere (ionosphere) are shown, which consist in the absence of instrumental means of direct measurements of the composition electron-ion trap combined density sensor of the atmosphere at altitudes from 150 to 500 km. In this article describes the possible design and study of the electron-ion trap combined density sensor and the composition of the upper atmosphere and simulation of the processes occurring in it. The simulation of the electric field between the electrodes of the trap and the motion of charged particles in it is carried out. The calculation of the maximum speed and energy of the particles, which the trap holds all charged particles, even in the case of the most unfavourable direction of their speed – along the gap between the electrodes. It is shown that this critical energy does not depend on the particle mass, and the probability of passage of charged particles with energy above the critical energy through the trap is estimated.

Keywords: earth atmosphere, upper layers, air density and composition, measurements, sensor, ionization, vacuum gauge converter.

Introduction:

Measuring the density and composition electron-ion trap combined density sensor of the earth's atmosphere is extremely important for understanding the complex processes occurring in the upper atmosphere under the influence of solar and galactic radiation, for predicting the further development of the global ecosystem of the Earth, its interaction with solar radiation and near space, for studying the anthropogenic impact on it, as well as for the further development of near space, which is becoming increasingly involved in human activities.

However, direct measurements of the density and composition of the earth's atmosphere were studied only to heights of 30-70 km, i.e. within the troposphere and stratosphere (using equipment installed on high-altitude aircraft, stratospheric balloons and geophysical rockets) .[1]

Strain gauges were successfully used at altitudes up to 20 km to measure atmospheric pressure (air density), at altitudes up to 50-70 km – thermoelectric vacuum gauges. To measure the composition of

the air at these altitudes – spectrometric instruments, but at high altitudes-up to 500-1000 km, where the pressure becomes less than 1 Pa. [2]

The structure of the ionosphere undergoes daily, seasonal, and solar cycle changes. Significant ionospheric electric currents and wave processes occur in it. The registration of these changes, the construction of local altitude profiles of the concentration of neutral and charged particles (electrons, protons and ions of various types), their dependences on the latitude and longitude of the area, time of day, season, solar activity and other factors are extremely important for building local and global models the state of the upper atmosphere and a deeper understanding of the processes occurring in them. That is why direct instrumental studies of the density and composition of the atmosphere at these altitudes are so important, carried out using scientific equipment placed on manned and unmanned satellites. But the satellite's orbits are located at altitudes of more than 350-400 km. [3]

And altitudes from 150 to 500 km, where the most important processes of interaction of the atmosphere with solar and galactic radiation occur, were the least studied. Therefore, it is at these sites that equipment placed on micro-and nanosatellites launched from the international space station (ISS) during astronauts ' spacewalks or from manned or unmanned spacecraft or geophysical rockets, and orbiting the Earth in gradually decreasing orbits for several months, can play an important role in research. However, it is not possible to use existing industrial ionization vacuum sensors for these purposes due to a number of reasons: significant weight and size characteristics and power consumed from the power source, low mechanical strength and insufficient vibration resistance of all ionization primary converters with a hot cathode. But the most important problem is undoubtedly the influence of charged particles on the readings of these sensors in the ionosphere.[4]

The main problem preventing the use of industrial vacuum ionization transducers to measure the density of air in the ionosphere is the high concentration of charged particles in it: ions, free electrons and protons. Given that the coefficient of ionization of neutral particles in ion-electron Converter cold cathode is very small, getting in the active zone of ionization of the Converter from ambient air a substantial fraction of the ions, the concentration of which in the ionosphere reaches a few percent of the number of neutral particles, can distort the readings on the vacuum gauge dozens of times. To avoid this, an electron-ion trap is installed before entering the active zone of the Converter. In this case, the ionization sensor readings will be correct, because the ion current of the sensor will be determined only by the concentration of neutral atoms and molecules, and gamma radiation, from which the trap does not protect and the intensity of which at these heights is significantly higher than at the earth's surface, will only facilitate the ignition of the discharge in the working area of the sensor, without affecting its readings. [5]. At the same time, the trap of charged particles serves not only to increase the reliability of the vacuum transducer readings, but also allows to determine the concentration of negatively charged particles (mainly electrons) and positively charged particles: ions and protons in parallel with the determination of the concentration of neutral particles. The same high voltage source as the vacuum transducer must be used to power the trap.

In this series of articles, we consider the possibility of creating a combined miniature sensor density and composition of the upper atmosphere, allowing the ionosphere to separately measure the concentration of neutral and charged particles (electrons, ions and protons) and suitable for installation on nanosatellites. The sensor consists of an inversely magnetron vacuum transducer, which allows to measure the concentration of neutral particles and electron-ion trap, which does not pass charged particles into the active zone of the vacuum transducer, which preserves the reliability of its readings and at the same time allows to determine the concentration of charged particles. Mathematical modeling of its operation in the ionosphere is carried out and its main characteristics are determined on the basis of experimental study of its model sample in a vacuum chamber.

An exemplary design of a combined Converter-density and composition of the air environment
This Converter is an upgraded vacuum-gauge Converter, equipped with an electrostatic trap for charged particles. The trap should intercept all charged particles contained in the ionosphere, not passing them into the active zone of the vacuum transducer, but completely pass their neutral atoms and molecules.

Schematically, the design of such a trap of charged particles attached to the vacuum transducer is shown in 'figure 1'.
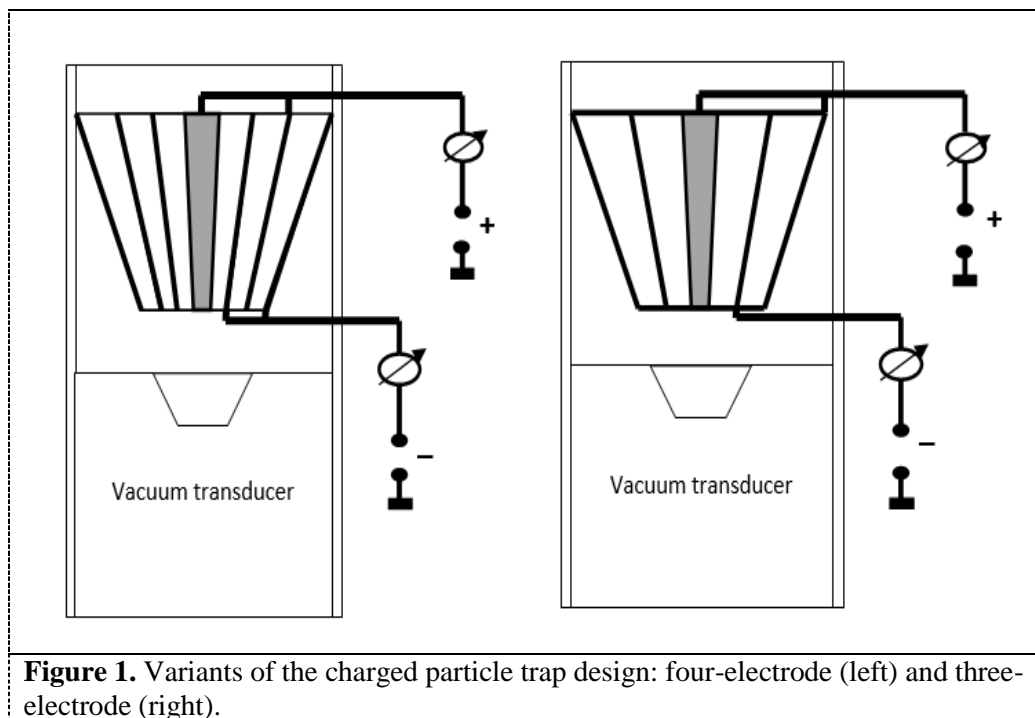

Figure 1. Variants of the charged particle trap design: four-electrode (left) and three-electrode (right).

The trap itself consists of several electrodes in the form of nested hollow truncated cones connected to a high-voltage DC power source. Positive electrodes (anodes) collect negatively charged particles (electrons and negative ions), and negative electrodes (cathodes) – positively charged particles (positive ions and protons), the Corresponding electric currents are measured by additional measuring channels, which makes it possible to determine the concentration of positively and negatively charged particles. The upper end of the trap is open to the outside environment. Charged particles entering the interelectrode space of the trap are deflected by a strong electric field to the electrodes (negative to the anodes, positive to the cathodes).

Accordingly, only neutral particles fall into the working volume of the vacuum transducer. This ensures the correctness of its readings proportional to the concentration of neutral atoms and molecules in the air. Thus, it is possible not to be afraid of difficulty of ignition of the discharge because of lack of the "seed" electrons necessary for its ignition. They will be much more than in the operation of such converters in ground conditions, since at these heights the gamma background is repeatedly increased, and when interacting with the substance of gamma rays of the structural elements of the Converter (mainly the magnet and the pole overlays) from their inner wall layers will fly into the working volume of the Converter electrons knocked out of atoms due to the photoelectric effect, Compton effect and the effect of the birth of electron-positron pairs. This will facilitate the extension of the transducer measurement limit to the lower side. Thus, this combined Converter will correctly measure not only the concentration of neutral atoms and molecules in the ionized air, but also the concentration of negatively charged particles (electrons and negative ions) and positively charged particles (positive ions and protons).

Macroscopic mathematical model of charged particle trap.
The calculation of the charged particle trap is possible both with the use of an analytical approach and with the use of standard electric field simulation programs. Since high accuracy of this model is not required, we will use an analytical approach. Its errors will be determined by the edge curvatures of

the electric field not taken into account. But, since the gaps between the electrodes are much smaller than the height of the electrodes, these errors will be small.

To calculate the electric field in the interelectrode space, we will use the known formula of the electric field of a coaxial cylindrical capacitor: [6]

$$E(h) = \frac{U}{r \ln \dfrac{R_l(h)}{R_u(h)}} \tag{1}$$

where U is the voltage on the capacitor plates;
- r – current radius;
- $R1$ and $R2$ are the radii of the inner and outer electrodes, respectively.
- $E=$ electric field.

In the proposed design of the trap, the gaps between adjacent electrodes are reduced with a decrease in height, which provides an increase in the electric field as the particles penetrate deeper into the trap.

To calculate the field in such a design, it is possible to replace conical surfaces with cylindrical ones with stepwise decreasing diameters, as shown in 'figure 2' (left). In this case, the expression (1) is valid for each step of such surfaces. From it is easy to go to the continuous function $E(h)$, if you set the linear functions $R_l(h)$ and $R_u(h)$, where h – the current height of the cones: [7]

$$E(h) = \frac{U}{r \ln \dfrac{R_l(h)}{R_u(h)}} \tag{2}$$

The height of the trap will be divided into 10 sections, and the calculations will be carried out for the radii corresponding to the middle of these sections. The formula for finding the radii of any of these cones at an arbitrary height h is easy to obtain from the geometric construction shown in 'figure 2' (right). Based on the geometric construction shown in 'figure 2' (right), current radii of the cones of the trap is calculated as: 'figure 2' (right), current trap cone radii should be calculated as: [7]

$$R(h) = R_l + \frac{R_u - R_l}{H} \cdot h \tag{3}$$

where: $R(h)$ is the radius of the cone at an arbitrary height h;
- R_u is the radius of the cone at the upper end;
- R_l is the radius of the cone at the lower end;
- R_{av} is the radius of the cone at the average end;
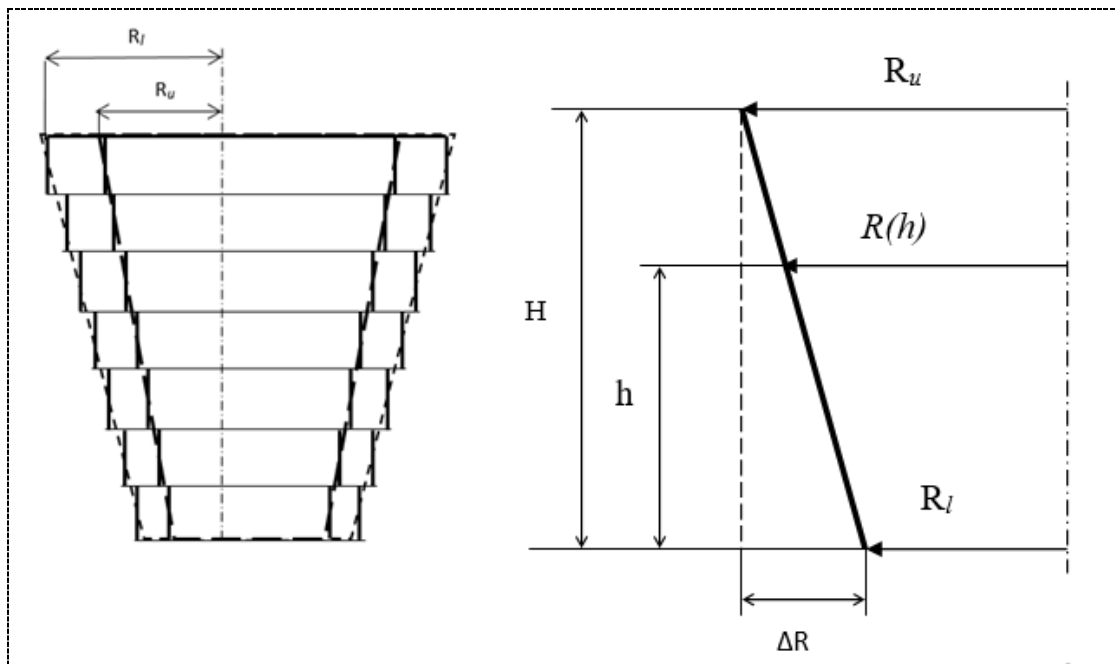- H is the total height of the truncated cone.

Figure 2. The approximation of conical surfaces of stepped cylindrical surfaces (left) and the determination of the radii of the conical electrode at an arbitrary height h (on the right).

For a four-electrode trap, the geometric dimensions of the electrodes are shown in table 1 (the thickness of the electrodes is assumed to be 0.1 mm).

where: D1, Du is the refer to dimensions of the electrodes

Table 1. Geometric dimensions of the charged particle trap

№ cones		1	2	3	4
upper	D_l, mm	19	15	11	7
	D_u, mm	18,8	14,8	10,8	-
lower	D_l, mm	10	7	4	1
	D_u, mm	9,8	6,8	3,8	-

Take the total height H for all cones equal to 40 mm and divide it by height into 10 sections, and the current radii will be found for the middle of these sections. Then for each section it is possible to approximate conical surfaces cylindrical and for calculation of an electric field of each section to apply expression (2). The value of the electric voltage is the same as for the vacuum transducer and equal to 1000 V. Below (table. 2 and 'figure 3') here are the results of the calculation of the electric field for one of the pairs of electrodes (These measurements are calculated in units of mm).

where: E_l is the electric field lower;

- E_u is the electric field upper;
- E_{av} is electric field average.

For the first cone (inner surface) $R_u = 9.4$ mm, $R_l = 4.9$ mm H for all cones 40 mm, **h** is shown in the tables. Consequently, for the height $h = 38$ mm we get for the first cone (inner surface)

$$R_2(38) = 4,9 + \frac{9,4-4,9}{40} \cdot 38 = 9,175$$

For the minimum height $h=2$ mm, we obtain:

$$R_2(2) = 4,9 + \frac{9,4-4,9}{40} \cdot 2 = 5,125$$

Table 2. Calculation of the electric field for the first pair of electrodes

h, mm	$R_1(h)$, mm	$R_2(h)$, mm	$R_{av}(h)$, mm	E_l, B/mm	E_u, B/mm	E_{av}, B/mm
38	7.3	9.175	8.237	476	598	537
34	6.9	8.725	7.812	490	619	554
30	6.5	8.275	7.387	501	638	569
26	6.1	7.825	6.962	513	658	585
22	5.7	7.375	6.535	525	680	602
18	5.3	6.925	6.112	541	707	624
14	4.9	6.475	5.687	555	734	644
10	4.5	6.025	.262	568	761	664
6	4.1	5.575	4.837	584	794	689
2	3.7	5.125	4.412	599	829	714

For charged particles entering the space between the electrodes, the case is critical when they fall along the gap between the electrodes. In all other cases, the particles collide with the electrodes and are either neutralized (if the electrode has the opposite charge) or repelled from it (if they have the same charges) and fly to the opposite electrode and there are neutralized. Therefore, below is the calculation of the limit energies of charged particles for the critical case when their initial velocity is directed along the gap Between the electrodes.

Figure 3. Dependences $E=f(h)$ for the first pair of electrodes of a four-electrode trap
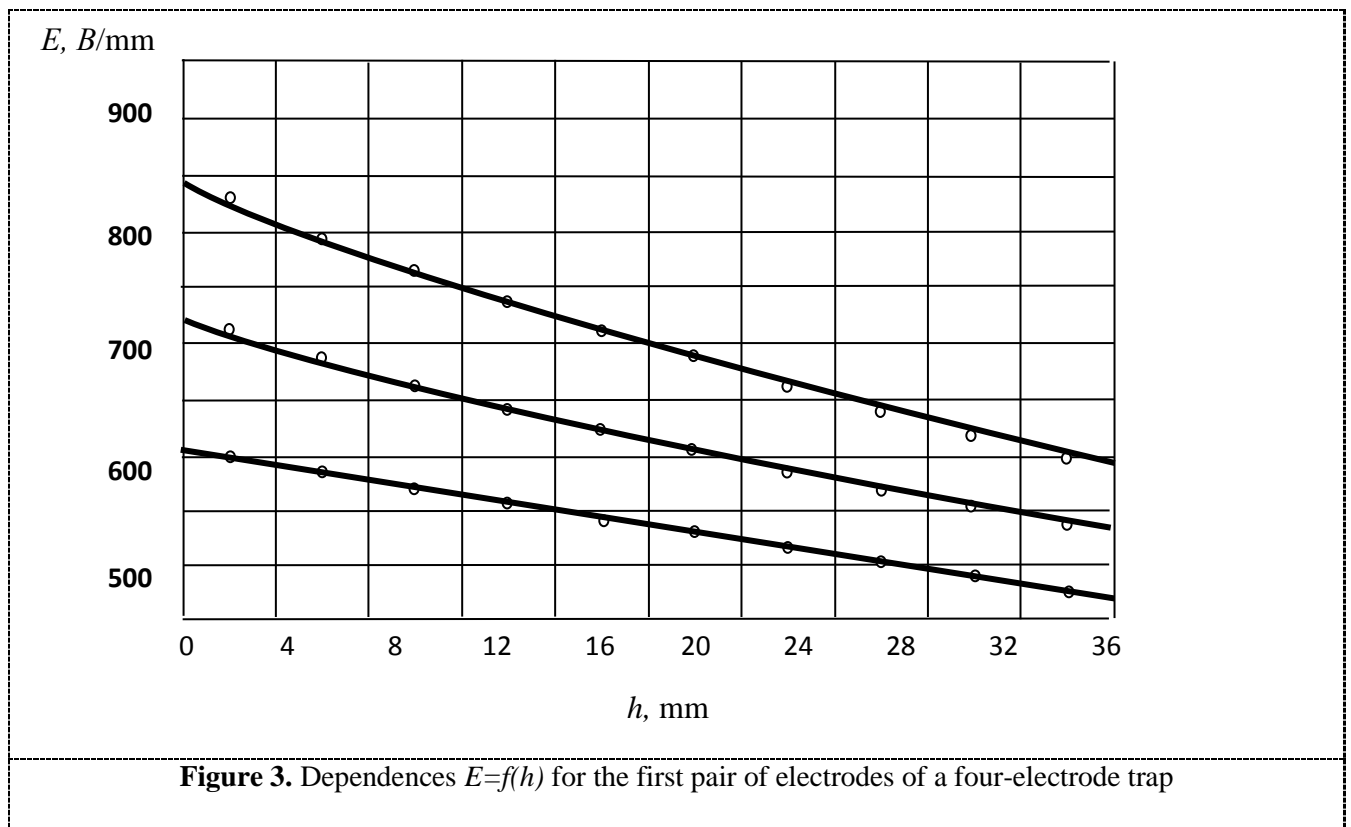
The calculation of the maximum energy of charged particles trapped
When moving in a transverse electric field, a force acts on the charged particle, deflecting it in the transverse direction. Even in a uniform electric field, the charged particle moves uniformly accelerated, and in this case the field increases as it approaches the internal electrode and as the

particle sinks into the trap. However, given that high accuracy is not required, we assume that the field is uniform and equal to the corresponding mid-gap between the electrodes at half the height of the trap. Given these conditions, the particle will move along the r axis uniformly accelerated [8].

$$r = \frac{1}{2}mqEt^2 \qquad (4)$$

Assuming that during this time the component of the particle velocity along the z axis remains unchanged and equal to *V*, we find the current height of the trap *(H – h) =VT*, at which the particle reaches the opposite electrode.

$$H - h_T = V\sqrt{\frac{2md}{qE}} \; . \qquad (5)$$

Passing from the velocity to the energy of the particle $E_p = \frac{mV^2}{2}$, where $V = \sqrt{\frac{2E_p}{m}}$

Receive:

$$(H - h_T) = \sqrt{\frac{4E_p d_{av}}{qE}} \qquad (6)$$

Finding out E_p of the particles obtained

$$E_p = \frac{(H-h_T)^2 qE}{4d} \; . \qquad (7)$$

At $h_T = 0$, we obtain the maximum kinetic energy of the particles captured by this trap in the most unfavourable case, when their velocity is directed along the gap between the electrodes of the trap:

$$E_{p\,max} = \frac{H^2 qE}{4d_{av}} \qquad (8)$$

As you can see, it no longer appears the mass of the particle, but only its charge. Therefore, for both electrons and single-charged ions, the limit energy at which they will be trapped will be the same. This is an important conclusion because it allows us to determine the boundary energy of any charged particles. Substituting in (10) numerical values $H = 40$ мм, $q = e = 1.6 \cdot 10^{-19}$, $d_{av} = 1,65$ мм, $E = 620$ V/mm (for the first pair of electrodes), we obtain

$$E_{p\,max} = \frac{40^2 \cdot 1,6 \cdot 10^{-19} \cdot 620}{4 \cdot 1,65} = 2,4 \cdot 10^{-14} = 150 \,\text{Kev}$$

where: *e* is the electric charge $= 1.6 \cdot 10^{-19}$

Of course, this expression is approximate, since the electric field strength will increase as the particle approaches the oppositely charged electrode and moves deeper into the trap, since *E* depends on both *r* and *h*. This means that the real value of the critical energy of the particles captured by the trap will be higher than this estimate.

But the most important thing is that here we consider the most unfavourable case of the direction of the particle velocity relative to the position of the trap. In fact, the direction of particle velocity relative to the trap can be considered chaotic, since the position of nanosatellites, which is supposed to place the projected sensor, relative to the earth's surface is not stabilized, and the particles themselves move quite chaotically, although the earth's magnetic field affects the charged particles within the ionosphere, causing them to move in cyclotron orbits along the magnetic field lines. But in relation to the velocity vector of the spacecraft itself, the directions of their velocity can be considered equally

probable. This means that the probability of the above case of the direction of the initial velocity of the particle along the gap between the electrodes can be estimated as the ratio of the solid angle θ, in which in the absence of the field the particle would not collide with the trap electrodes, to the solid angle 2π. Given the trap geometry, this angle θ can be estimated to be approximately 1^0 for a four-electrode trap and 1.5^0 for a three-electrode trap. Therefore, even if we limit the solid angle at which the particle can fall into the trap 120 degrees (instead of 180^0), the probability of coincidence of the particle velocity with the direction of the gap between adjacent electrodes can be estimated as 0.8 % for a four-electrode trap and 1.25 % for a three-electrode trap. This means that with a probability of about 99 %, this trap will capture charged particles of any energy, and only for the remaining 1 % of the particles, the energy of the captured particles will be limited to 0.15 MeV. Therefore, it is safe to say that this trap will delay and neutralize almost all charged particles. Given that the concentration of charged particles in the ionosphere is about 50...1000 times lower than that of neutral particles, the error in measuring the concentration of neutral particles due to the neutralization of charged particles and their entry into the active zone of the vacuum transducer will not exceed one percent.

Conclusion

   Summarizing the development of the combined sensor of the density and composition of the upper atmosphere (ionosphere), the following conclusions can be drawn:
1. Within the ionosphere, all characteristics of the atmosphere, including density, composition, temperature, degree of ionization, radius of cyclotron rotation in the earth's magnetic field, etc. are highly variable and depend not only on the height, but also on the time of day, time of year, latitude, solar activity and many other factors, the influence of most of which are poorly studied due to the complexity of direct measurements at these heights and the lack of adequate measuring instruments suitable for installation on micro-and nanosatellites. This determines the relevance of the development of such tools.
2. The main factors hindering the use of existing industrial devices (ionization vacuum meters and mass spectrometers) for these purposes are a high degree of ionization and a strong rarefaction of the upper atmosphere. Especially difficult for direct measurements are the heights from 150 to 500 km, where the most complex and poorly studied processes of interaction of the earth's atmosphere with solar and galactic radiation, affecting both the weather and long-range radio communication and, ultimately, the entire ecosystem of the earth, and it is at these heights that the most effective scientific equipment can be placed EA micro-and nano-satellites.
3. The experimental studies of the prototype of this transducer in a vacuum chamber made it possible to determine the real ionization coefficient of neutral particles in this transducer and confirmed the correctness of the developed mathematical model of the processes occurring in it.

Acknowledgements

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