Combined Vacuum Sensor For Measuring the Density and Composition of the Ionosphere

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Abstract- A design of an electron-ion trap for a sensor of the density and composition of the upper atmosphere (ionosphere), intended for placement on nanosatellites, is proposed. It allows you to capture charged particles of any energy and direction of their speed, dividing them by the sign of charge and energy. This ensures the correct operation of the vacuum gauge Converter of this sensor and the ability to register the density of charged particle flows, dividing them by sign and energy. The calculation of the maximum energy captured by the upper system of the trap electrodes and the estimation of the values of the trap currents in the required range of heights was performed. High-energy particles that pass through the upper system of electrodes are captured by the lower system of electrodes.

Keywords: ionosphere, density, composition, experimental studies, inverse-magnetron converter, modeling.

INTRODUCTION

The relevance of the development of a small-size ionospheric density and composition sensor suitable for nanosatellite separation was substantiated, the design of a cold-cathode vacuum transducer developed for it was described, and calculations were made of the crossed electric and magnetic fields formed in its core and the processes of ionization of neutral atoms and air molecules occurring in it. This article presents the design and calculation of processes occurring in an electron-ion trap, calculates the energies of charged particles captured by the upper system of the trap's electrodes, and estimates the value of possible currents through its electrodes.

Design of the upgraded vacuum gauge

The most suitable vacuum ionization transducer design for use in the ionosphere is the cold cathode inverse magnetron design. Such a converter has high mechanical strength, resistance to vibration, and significantly lower power consumption than converters with a hot cathode, while providing the ability to measure pressure from 1 to $10^{-6}$ Pa, which corresponds to altitudes from 80 to 500 km. The main disadvantages of industrial sensors of this type with regard to the use of micro- and nano-satellites are significant weight and size characteristics and rather high energy consumption due to energy losses at a high-resistance ballast resistance connected in series with the converter.

But these shortcomings are quite surmountable. It is much more difficult to exclude the influence on its readings of charged particles, the concentration of which at these heights is very high. Given the negligible ionization coefficient of neutral particles in the active zone of this transducer (of the order of $10^{-6}$), penetration of charged particles from the
external medium into its active zone can distort its readings by a factor of tens. To get rid of their influence, it is necessary to equip this transducer with a trap of charged particles so that only neutral atoms and molecules can get into the working area of the vacuum gauge itself. In this case, the readings of the ionization sensor will be correct. If, at the same time, the currents determined by the neutralization of charged particles on the trap electrodes are measured, then the concentration of positively charged particles (positive ions and protons) and negatively charged particles (electrons and negative ions) can be additionally determined separately.

The design of the prototype vacuum gauge transducer (without an electron-ion trap) is shown in Figure 1.

![Fig. 1. The design of the prototype vacuum gauge inverse magnetron converter](image)

Its magnetic system consists of three commercially available ring neodymium magnets joined by unlike poles and pole plates. Moreover, the force of attraction of the rings to each other and the pole plates to them is so great that the assembly does not require additional fastening.

**Modeling of electric and magnetic fields in the working area of the converter**

The anode and cathode of the converter form a coaxial system, the electric field strength of which from the current radius is determined by the formula

$$E = \frac{U}{r \ln \frac{R_1}{R_2}}$$  \hspace{1cm} (1)

$R_1 =$ the radius of the anode is (0.75 mm); $R_2 =$ is the cathode radius of (6.3 mm).

For the average diametrical cross section of the active zone of the transducer, the influence of the pole plates under the cathode potential cannot be taken into account, since for the middle cross section it will be mutually compensated, and the electric field vector will be directed along the radius, which allows calculating the field in this section according to the formula (1). However, as we approach the pole plates, the longitudinal component of the field will increase. Due to this component, the electrons flying to the pole plates will return to the central zone. This is very important, since the magnetic field does not affect the longitudinal component of the electron velocity and cannot prevent the loss of electrons (with their neutralization at the anode) emitted from the central zone of the converter.
To determine the boundaries of the central zone, the calculation of the electric and magnetic fields of the transducer in the active zone was carried out in the COMSOL system. The calculation results are presented in Fig. 2 (left for the electric field, right for the magnetic). In this figure, taking into account the symmetry of the electrode system of the converter, the field configuration for one quarter is shown. electrode system (arrows indicate the directions of the lines of electric field and magnetic induction).

Considering that already at a distance of (2 mm) from the middle section, the longitudinal component of the electric field begins to appear, caused by the influence of the pole plates and as it approaches the pole plates, it grows, the electrons flying into this zone will be pushed back to the central zone. As for the magnetic field, it is already almost uniform at a distance of 1 mm from the end of the pole plate. Therefore, in further calculations, the magnetic field in the working area of the converter can be considered homogeneous with an induction of (0.1 T) (the magnitude of the induction in the working gap of the magnetic system was measured experimentally).

To create the optimal electric field strength, providing impact ionization of neutral atoms in the working area of the converter, an anode voltage of (1000 V) was sufficient. The results of calculating the electric field in the interelectrode space for the central section are presented in (Table 1 and Fig. 3).

| $r_i$ [mm] | 0,75 | 1,0 | 1,5 | 2,0 | 3 | 4 | 5 | 6,3 |
|------------|------|-----|-----|-----|---|---|---|-----|
| $E_i$ [V/mm]| 626  | 470 | 313 | 235 | 157 | 118 | 94 | 75  |

Figure 3. The dependence of the electric field on the current radius in the middle section of the active zone of the Converter
“Seeding” electrons in the active zone of the transducer in the presence of an electron-ion trap are formed in the active zone due to the emission of electrons from the near-wall layers of the magnet and pole plates due to the interaction of gamma and X-ray radiation (which at these heights is significantly stronger than at the surface Earth). It is only important to prevent field emission in the gap between the lateral surface of the pole plates and the anode, where the electric field is stronger than in the working area and the magnetic field is no longer perpendicular to the electric field and cannot prevent the electron field emission electrons from reaching the anode.

**Analysis of the motion of electrons and ions in crossed electric and magnetic fields**

The absolute value of the average electron velocity, and hence their energy, will be determined by the additive sum of the thermal (chaotic) and drift velocities, which means that the electron energy will also be composed of the thermal and drift components. Since the electrons receive additional energy due to the electric field, it is precisely the electron drift velocity that is important for ionization. The components of the drift velocity along the x and y axes perpendicular to the longitudinal z axis are determined by the expressions [5, 6]:

\[
\begin{align*}
V_{dx} &= -\mu_e \frac{E_x}{1 + \frac{\Omega_c}{\nu_{en}}} V_{dy} = \mu_e \frac{\Omega_c}{1 + \frac{\Omega_c}{\nu_{en}}} E_y, \\
V_{dy} &= \mu_e \frac{\Omega_c}{1 + \frac{\Omega_c}{\nu_{en}}} E_y.
\end{align*}
\]

(2)

Here \( \mu_e = \frac{e}{m_e \nu_{en}} \) - electron mobility; \( \Omega_c \) - cyclotron rotation frequency; \( \nu_{en} \) is the collision frequency of electrons with neutral particles.

As follows from these expressions, the drift velocity will depend not only on the electric field strength, but also on the ratio of the cyclotron frequency of rotation of electrons in the magnetic field and the frequency of their collisions with neutral gas particles. Therefore, to determine the electron drift velocity in crossed fields, it is necessary to find the electron cyclotron rotation frequency \( \Omega_c \) and the frequency of their collisions with neutral particles \( \nu_{en} \).

In [6], for the cyclotron frequency, a general formula is given that is suitable for any charged particle:

\[
\Omega_c = \frac{|q| B}{m},
\]

(3)

where \( q \) is the particle charge in (C); \( m \) is its mass in (kg); \( B \) - magnetic field induction in (T).

As applied to an electron, the formula will take the form

\[
\Omega_c = \frac{eB}{m_e} = \frac{1.6 \cdot 10^{-19}}{0.911 \cdot 10^{-30}} = 1.756 \cdot 10^{11} \cdot B
\]

(4)

Substituting the magnetic induction value equal to (0.1 T), we obtain

\[
\Omega_c = 1.756 \cdot 10^{11} \cdot 0.1 = 1.756 \cdot 10^{10} \text{ [s].}
\]

According to [3], the mean free path of electrons (we denote it by \( \lambda \) to distinguish it from the mean free path of neutral gas particles, which is denoted by \( \lambda \)) is about one-fold as long as the mean free path of the gas particles themselves under the same conditions. In the altitude range from (150 to 500) km: the mean free path of neutral gas particles is from (3.37 m to 14.7) km. Consequently, the mean free path of electrons will be in the range from (19m to 83)km. This is several orders of magnitude larger than the size of the active zone of the transducer, which means that the movement of electrons in the interelectrode space of the transducer is quite acceptable to consider as the movement of free electrons in a
vacuum in the presence of corresponding electric and magnetic fields. Now you can calculate the drift velocity and the
drift energy of electrons. Using expression (2) for the orthogonal components of the electron drift velocity in crossed
electric and magnetic fields and taking into account the fact that we can decompose the electron orbital velocity (which
interests us) into these components at each moment of time, we will find it as the vector velocity module:

\[ V_{\perp\beta} = \sqrt{V_{en}^2 + \frac{\mu_e E}{m_e v_{en}}} \]

Substituting here \( \mu_e = \frac{e}{m_e v_{en}} \), we get:

\[ V_{\perp\beta} = \frac{e}{m_e v_{en}} \frac{E}{\sqrt{1 + \frac{\omega_e^2}{v_{en}^2}}} \]

The values of \( e \) and \( m_e \) in this expression are constant. Substituting their values, we finally obtain \( k \) (hereinafter, we omit
the index \( \perp \) determining the direction of the drift):

\[ V_{\phi} = \frac{1.6 \cdot 10^{-19}}{911.1 \cdot 10^{-10}} \frac{E}{v_{en}} \cdot \frac{1.756 \cdot 10^{11}}{v_{en}} \frac{E}{v_{en}} = 1.756 \cdot 10^{11} \frac{E}{v_{en}} \]

Substituting the numerical values of \( (\omega_e) \) and \( (v_{en}) \), we find that the ratio of their squares is more than \( 10^6 \). This means
that in the root expression (7) we can neglect unity and then it will be even more simplified:

\[ V_{\phi} = \frac{1.756 \cdot 10^{11}}{v_{en}} \frac{E}{v_{en}} \]

The cyclotron rotation frequency(\( \omega_e \))of the electrons depends only on induction in the air gap and for the induction
value (B = 0.1 T) is \( (\omega_e = 1.756 \cdot 10^{10} \text{ s}^{-1}) \). Accordingly, instead of (8), we can write:

\[ V_{\phi} = \frac{1.756 \cdot 10^{11}}{1.756 \cdot 10^{10}} = 10E \]

Given the values of the drift velocity\( (V_{\phi}) \)and taking into account the conversion factor \( (K_e = 0.625 \cdot 10^{19}) \) from (J to
Ev), it is easy to calculate the electron drift energy:

\[ \varepsilon_e = \frac{m_e V_{\phi}^2}{2} = \frac{0.9111 \cdot 10^{19} \cdot 0.625 \cdot 10^{10}}{2} \cdot \frac{1.756 \cdot 10^{10}}{911.1} = \frac{0.2851 \cdot 10^{10} v_{\phi}^2}{2} \]

In this case, the average radius of the Larmor (cyclotron) orbits of the cycloidal rotation of electrons in a transverse
magnetic field will be equal to:
\[ r_c = \frac{V_\varnothing}{\omega_c} \]

The results of calculations of the drift velocity \( V_\varnothing \), drift energy \( \omega_\varnothing \) and the radius of cyclotron orbits \( r_c \) from the values of the current radius are presented in Table 2. In it, the minimum value of the current radius is assumed to be (0.8 mm), which is (0.05 mm) more than the radius of the anode, and the maximum value is equal to 6 mm, which is (0.3 mm) less than the inner radius of the cathode (near the cathode, the electric field is close to uniform). From this table it follows that in the anode zone (for values of the current radius from (0.8 to 2) mm, the drift energy of electrons is sufficient even for direct ionization of neutral air particles, and taking into account multi-stage ionization (excited atoms), the ionization zone expands to almost the entire active zone converter (up to the current radius of 5 mm).

| \( r_c [mm] \) | 0.8 | 1.1 | 1.52 | 2 | 3 | 4 | 5 | 6 |
|----------------|-----|-----|------|---|---|---|---|---|
| \( E \times 10^5, [v/m] \) | 5.2 | 4.8 | 3.17 | 2.36 | 1.62 | 1.18 | 0.95 | 0.8 |
| \( V_\varnothing \times 10^5, [m/s] \) | 50 | 48 | 31.32 | 23.53 | 15.9 | 11.31 | 9.41 | 7.58 |
| \( \omega_\varnothing, [ev] \) | 71.4 | 64 | 56.1 | 31.51 | 14.21 | 7.62 | 5 | 3.21 |
| \( r_{ce}, [mm] \) | 0.3 | 0.28 | 0.19 | 0.16 | 0.11 | 0.06 | 0.06 | 0.05 |

Ions under the influence of an electric field will drift to the cathode. To calculate the ion drift velocity, the same formulas are used as for electrons, but instead of the electron mass \( m \), the mass of the air molecule (averaged between the nitrogen and oxygen molecules) is substituted, instead of the frequency of collisions of electrons with neutral molecules \( \nu_n \) the frequency of collisions of ions with neutral molecules \( \nu_i \), and instead of the frequency of cyclotron rotation of electrons \( \omega_e \), the frequency of cyclotron rotation of ions \( \omega_i \). The calculation results show that, as expected, the ion and electron drift velocities coincide (since the charges are the same in magnitude, and there are practically no collisions of ions with neutral molecules and with each other in the range of measured pressures), but the energies and radii of cyclotron orbits for ions are approximately 4 orders of magnitude higher than for electrons (since it is precisely the number of times that the mass of an ion is greater than the mass of an electron). Therefore, all ions immediately after their formation will leave the active zone of the transducer, neutralizing at the cathode, i.e., the magnetic field will not be able to prevent them from reaching the cathode. Moreover, since the mean free path for ions is many times greater than the transverse dimensions of the active zone of the transducer, when moving toward the cathode, they will not collide with neutral particles, or with electrons, or with each other.

The processes of ionization of neutral particles in the core vacuum gauge

The threshold energy of air ionization (taking into account the ratio between nitrogen and oxygen) is (33.9 eV). Consequently, direct single-stage ionization of air by electrons becomes possible when the values of the current radius of the active zone of the transducer are less than (2 mm) (see Table 2), and the maximum probability of ionization will occur with values of the current radius from (0.8 to 1.5) mm [the radii of cyclotron orbits of electrons are from (0.25 to 0.15 mm)]. But in this case, only single-stage ionization is taken into account, but in reality, multi-stage ionization will also occur. The mechanism of multistage ionization consists in a high probability of excitation of air molecules already in the range of electron energies above 2eV, and for excited molecules, the ionization potential decreases just by the value of the excitation energy. In this case, the number of exciting collisions of electrons with neutral particles is several times higher than the number of ionizing collisions both for electrons with an energy of lower ionization potential and for electrons with an energy of higher ionization potential. Although the lifetime of excited molecules in the general case is short (of the order of \( 10^5 \) s), however, for nitrogen molecules and oxygen molecules, it is possible to excite metastable states with a lifetime of much more than 1 s, and the cross section of these reactions is quite high (approximately equal to 10 Barn) [5]. Accordingly, multistage ionization becomes possible in almost the entire active zone of the converter.
The process of ionization of neutral atoms in the active zone of the inverted-magnetron converter develops in an avalanche-like time, since with each ionizing collision of an electron with a neutral particle an additional electron is knocked out of it, i.e., with each ionizing collision, the process of multiplication of free electrons occurs, which are accelerated by an electric field lead to additional ionization. An avalanche-like increase in the number of ionizing collisions occurs until a dynamic equilibrium is established between the number of electron / positive ion pairs generated per unit time and the number of ions and electrons neutralized at the anode and cathode of the converter. However, we are not interested in the transient process, but in the equilibrium state of the steady-state electric discharge in the converter, since we judge the pressure by the steady-state ion current.

Since the electron and ion currents are closed in a single external circuit, they must be the same. Then, knowing the ion drift velocity \( V_{\text{di}} \) and evaluating the average path length \( \text{lav} \) from the moment of birth to the moment of death (i.e., neutralization at the cathode), we can determine the average lifetime of them \( \tau_i \):

\[
\tau_i = \frac{\text{lav}}{V_{\text{di}}}
\]  

The ion drift velocity depends on the current radius of the transducer core. But since the zone of maximum ionization corresponds to the values of the current radius from 1 to 2 mm, we take its average, corresponding to the current radius of (1.5mm), & equal to \( (V_{\text{di}} = 31.3 \cdot 10^5 \text{ m/s}) \) (see table 2), and as mean path length is the distance between this zone and the inner surface of the cathode, which is \( \text{lav} = (6 - 1.5) = 4.5 \text{ mm} \). Substituting these values in (10) we obtain

\[
\tau_i = \frac{4.5 \cdot 10^{-3}}{31.3 \cdot 10^5} = 1.438 \cdot 10^{-9} \approx 1.44 \cdot 10^{-9} \text{ c}
\]

If the experimentally found conversion characteristic is known, i.e., the dependence of the ion current on pressure \( (I_i = \phi (p)) \), then it can be used to determine the number of ions arriving at the cathode of the converter per unit time:

\[
N^{i}_i = \frac{I}{e}
\]  

The superscript \( i \) here means that we do not determine the density of ions (i.e., their number per unit volume), but their number coming per unit time to the cathode of the converter. Considering that ions immediately after their formation reach the cathode, one can find the equilibrium amount of free ions in the plasma in the active zone of the \( (N^{\text{v}}_i) \) converter:

\[
N^{\text{v}}_i = N^{i}_i \cdot \tau_i
\]

To go to the average bulk density, it is necessary to divide this value by the volume \( V \) of the active zone of the converter:

\[
N^{\text{v}}_i = \frac{V}{N^{i}_i}
\]

The active zone of the transducer is a hollow cylinder with an outer diameter of \( (D = 12.7 \text{ mm}) \) (inner diameter of the cathode) and an inner diameter of \( d = 2 \text{ mm} \) (taking into account the radius of the cyclotron orbits of the electrons in the anode zone). The height of the active zone is equal to the distance between the pole plates and is \( (H = 10 \text{ mm}) \). Then its volume will be equal

\[
V = \frac{\pi}{4} (D^2 - d^2) H = \frac{3.14}{4} (12.7^2 - 2^2) \cdot 10.6 = 1308 \text{ m}\text{m}^3 = 1308 \text{ cm}^3
\]
We will find the ionization coefficient of gas molecules in the active zone of the transducer as the ratio of the number of ions formed in the active zone in the steady state determined by the measured ion current to the number of neutral particles in this volume:

\[ k_i = \frac{N_i}{N_n} \]  

(14)

Experimental studies of the transducer to find real values of the ionization coefficient were carried out which made it possible to obtain a minimum pressure of \(10^{-6}\) Pa. Altitudes from (150 to 500) km correspond to pressures from \((5 \cdot 10^{-4}\) to \(0.5 \cdot 10^{-6}\) )Pa. The experimentally obtained values of the ionization coefficient are presented in table 3.

Table 3. Values of ionization coefficient for pressures from \(10^{-6}\) to \(10^{-3}\) Pa

| \(p_i\) [Pa] | \(10^{-6}\) | \(10^{-5}\) | \(10^{-4}\) | \(10^{-3}\) |
|-------------|------------|------------|------------|------------|
| \(N_i\)     | 49.55      | 4.9-10^4   | 4.8-10^3   | 4.61-10^3  |
| \(N_n\)     | 4,62-10^7  | 7.1-10^8   | 9.1-10^9   | 1,52-10^11 |
| \(k_i\)     | 10,82-10^-7| 6,81-10^-7 | 5,25-10^-7 | 3,1-10^-7  |

From this table it follows that the ionization coefficient is very small and with increasing pressure the ionization coefficient monotonically (albeit slightly) decreases. This can be explained by the effect of the recombination of electrons and ions, since its probability increases with increasing pressure.

CONCLUSIONS

1. Direct instrumental studies of the upper atmosphere (ionosphere) are extremely important for building a model of the Earth’s ecosystem, 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 economic activities person. In this case, the least studied are the processes occurring at altitudes from (100 to 500) km, i.e., in the ionosphere. Their experimental study is most effective with the help of scientific equipment installed on micro- and nanosatellites. However, suitable tools for these purposes, adapted to autonomous functioning in near space conditions and suitable for installation on micro- and nanosatellites do not exist.

2. To study the density and composition of the upper atmosphere, a miniature sensor is proposed, consisting of a modernized vacuum-gauge inverse-magnetron converter, supplemented by an electron-ion trap that does not allow charged particles into its active zone, which, firstly, increases the reliability of its readings, and secondly, it additionally allows you to measure the concentration of positive and negative charged particles, which in the ionosphere is several orders of magnitude higher than their concentration at the surface of the Earth.

3. The modeling of electric and magnetic fields in the active zone of the vacuum gauge and the processes of impact ionization of neutral particles by electrons in crossed electric and magnetic fields.

4. 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.

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