Analysis of Some Reasons of Anomalous Electron Transportation in the Hall Thruster

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Sergey A. Oghienko[1], Anatoliy I. Oranskiy[2], Volodimir D. Olendarev[3] and Sergey V. Veryutin[4]
Zhukovsky National Aerospace University "Kharkiv Aviation Institute", Kharkiv, 61070, Ukraine

Abstract: Researches are curried out to find out the reasons of anomalous conductivity of plasma in the crossed electric and magnetic fields in conditions which are characteristic for a discharge interval of the Hall Thruster (HT). It is studied possible effecting electron transportation of a component of magnetic and electric fields, which are generated by HT operation and can be strengthened, and which have not been investigated enough. They are follows. 1) Azimuthal component of an electric field, which is generated owing to azimuthal heterogeneity of ion distribution. 2) Azimuthal component (can be strengthened artificially) of magnetic field self-generated by a discharge current. 3) Local electric field (central-symmetric, pulsing with frequency of 1…3 GHz, extent of which is of the order of electron gyro-radius), which can exist owing to cyclicity of electron movement and ionization process in this area. It was shown by numerical experiment that azimuthal heterogeneity of ion concentration $\Delta n_i/n_i$<1 % can cause transportation of electrons to the anode with characteristic velocity of the order $10^3…10^4$ m/s.

Nomenclature

B, B_r	=	magnetic field induction radial component
B_φ	=	magnetic field induction azimuthal component
E	=	electric field intensity
E_{loc}	=	local electric field intensity
I_d	=	discharge current
m	=	mass of electron
$\dot{m}$	=	mass flow rate
M_i	=	mass of ion
$n_{e,i}$	=	concentration of electron, ion
R_{gyro}	=	electron gyro-radius
T_e	=	electron temperature
V_{er}	=	electron velocity radial component
$V_{e.tr}$	=	electron cross-field transportation velocity
U_d	=	discharge voltage
φ	=	electric potential

[1] PhD, Senior Researcher, oghienko@yahoo.com, Department of thrusters and power plants of space vehicle.
[2] Dr, Professor, Head of the Engines Department of STC SPE KhAI, oranskiy@yahoo.com
[3] PhD, Senior Researcher, dsz@d4.khai.edu, Department of thrusters and power plants of space vehicle.
[4] Senior Researcher, dsz@d4.khai.edu, Department of thrusters and power plants of space vehicle.

I. Introduction

DEVELOPMENT of space and ground plasma technologies expands area of using of plasma accelerators and thrusters of various types. Among them so-called Hall (accelerator) thruster (HT) are features by its reliability, high value of ion current density, thrust efficiency and wide range of operation power. Basic HT circuit has been created more than 50 years ago and due to a good combination of operational characteristics of the first models (high operational efficiency, high reliability) HT is exploited already tens years. The base processes in HT are the next. Electrons emitted by the cathode move to the anode (20…30% of total discharge current) drifting in azimuthal direction in crossed longitudinal electric and radial magnetic fields in discharge chamber and ionized neutral atom. Ions berthing in discharge chamber are accelerated by the longitudinal electric and go out of the discharge chamber. Space positive charge of ion stream is neutralized by the electrons emitted by the cathode. For development and modernization of HT technologies in further it is necessary to improve the HT operation characteristics - to increase thrust efficiency reducing the electron component of discharge current and the plasma stream divergence, that in turn, helps to develop plasma technologies required HT. In initial detailed researches of processes in HT, curried out for its modernization, it has been established that density of an electronic current to the anode it is essential more than it was expected being based on classical conductivity [1]. In further, despite numerous experimental and theoretical researches, the mechanism of such anomalous electron conductivity in HT discharge has not been understood well enough. The understanding of conductivity of plasma outside of HT discharge chamber where a magnetic field still strong is especially difficult. In this paper researches are curried out to fine of the reasons of anomalous conductivity of plasma in the crossed electric and magnetic fields in conditions which are characteristic for a discharge interval of HT. It is studied influence of a component magnetic and electric fields to the electron transportation velocity and to discharge current what have not been investigated enough.

II. Influence of an azimuthal component of a stationary electric field to electron transportation

It was studied possible influence of azimuthal components of an electric field (stationary in time and a variable in an azimuthal direction), which is generated owing to azimuthal heterogeneity of ion concentration distribution in plasma of HT discharge interval, to the electron transportation velocity (look Fig. 1) and to the value of HT discharge current.

A. Hypothesis on ion heterogeneity compensation and electron cross-field transportation

Because of discrepancy of HT units manufacturing it is necessary to expect heterogeneity (a few percents) of distribution in an azimuthal direction of plasma-making gas. That, in turn, led to azimuthal heterogeneity of ionization intensity and to azimuthal heterogeneity of ion concentration. . The superfluous positive charge in such local areas cannot be compensated by a charge of electrons affected only by arisen azimuthal component of an electric field of monotonous character for the following reasons. Increasing of electron drift velocity in the area of heterogeneity of ion concentration of the extent $\approx 10^{-2}$ m ($R_{gyro} \approx 10^{-3}$ m) because of superposition arisen azimuthal component and before existed longitudinal component of an electric field would lead to decreasing of electron concentration in an azimuthal electron stream. As consequence, it would lead to an even greater difference in concentration of positive and negative charges. The superfluous positive charge in such local areas can be compensated by electron charge in the next way. It is assumed that when in HT it is exist areas of azimuthal heterogeneity of ion concentration $\Delta n_i/n_i \neq 0$, it is generated local (extent of the order of R_{gyro}) a non-uniform azimuthal component E_{loc} of electric field (look Fig. 1). Azimuthal velocity of electrons (drifting along the closed trajectories) can decrease because of electron scattering in the local field E_{loc}. As consequence, it is appears and increases heterogeneity of electron concentration $\Delta n_e/n_e > 0$ in local area and negative electron charge partially compensates a local charge of ions $\Delta n_e \leq \Delta n_i$ so many that in this area the electric field E_{loc} can exists as the self-consistent field. Besides, by scattering, it is going electron transportation across a magnetic field along electric (to the anode) with an average velocity $V_{e.tr}$. To check up a hypothesis and to calculate dependence $V_{e.tr}$ (B_r, E, T_e) numerical experiment was curried out in conditions when in plasma there are areas of azimuthal heterogeneity of ion concentration and local field E_{loc}.

B. Numerical experiment on ion heterogeneity compensation and electron cross-field transportation

Numerical experiment has been curried out as follows. In the discharge interval of HT it were set values of fields, energies and heterogeneities as a constants: $E \approx (0.37 \ldots 3.0) \cdot 10^4$ V/m, $T_{e0} \approx 3 \ldots 60$ eV, $B_r \approx (7.5 \ldots 45) \cdot 10^{-3}$ Tl; in the area of heterogeneity local potential drop varied from $\Delta\varphi \approx 0$ to $\Delta\varphi \leq T_e$, $\Delta n_i/n_i \leq 1/100$. Roughly it was suppose that thru value of temperature T_e is determined on initial T_{e0} and kinetic energy $m \cdot (E/B)^2/2/q$ of electron drift as $T_e \approx T_{e0} + m \cdot (E/B)^2/2/q$. In the first experiment the initial value of $\varphi_{max} << T_e$ was set and 10^5 electrons were

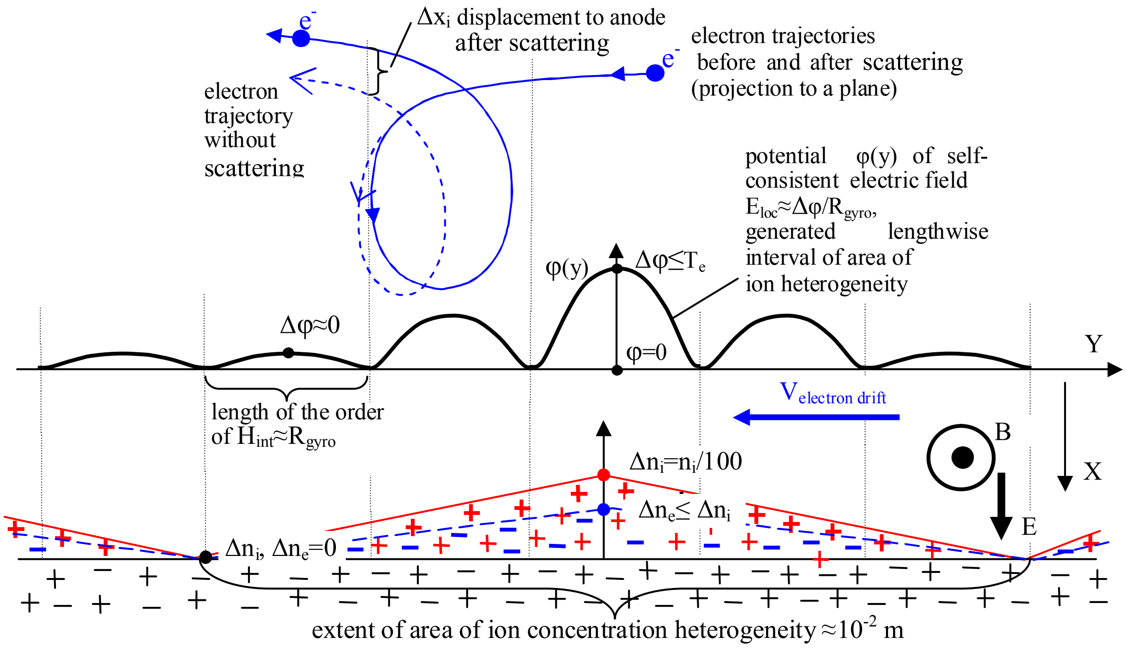

Figure 1. Model of electron scattering and displacement to anode process in the area of azimuthal heterogeneity of ions in HT plasma stream.

consistently "emitted" in area of ion concentration heterogeneity. The trajectory of electron movement was determined by integration of the equation of its movement in 3D Cartesian coordinates system with time step $3\cdot 10^{-12}$ s. The point of finish for everyone electron was on distance (along axis Y) multiple to H_{int} (look Fig. 1) so, that electron energy can change between points of start and finish, but stay the same in points of start and finish. It is necessary to notice, that in numerical experiment electron run along axis Y on the distance multiple to H_{int} implicitly means maxwell ization of electrons during run of length of the order of several $H_{int}\sim R_{gyro}$. At start of everyone i^{th} electron, its velocity was retrieved casually of a range 0 … $(3\cdot T_e\cdot q\cdot 2/m)^{1/2}$, in conformity with probability $f(v_{ei}, T_e)\cdot\Delta v_e$ at Maxwell distribution with density $f(v_{ei}, T_e)$ at temperature T_e. On finish it was recorded: time of movement $\Delta\tau_i$, displacement Δx_i along axis X (along an electric field) and it was calculated velocity of transportation of each i^{th} particle $v_{tri}=\Delta x_i/\Delta\tau_i$. Average velocity of transportation of all particles as $V_{tr}=(w_1\cdot v_{tr1}+\ldots+w_i\cdot v_{tri})$ in view of their range of velocity $(v_{ei}+\Delta v_e)$ and statistical weight $w_i=f(v_{ei}, T_e)\cdot\Delta v_e$ was determined. Take into account that density of electron flow in an azimuthal direction is constant $q_e=n_e\cdot V_{DR}$=const. Electron drift velocity can be calculated in numerical experiment as $V_{DR}=H_{int}/T_{mov}$, where average time of movement T_{mov} during interval H_{int} along axis Y is determined as $T_{mov}=(w_1\cdot\Delta\tau_1+\ldots+w_i\cdot\Delta\tau_i)$, is similar V_{tr}. Therefore change of electron concentration owing to change of drift velocity was determined as $\Delta n_e/n_e\approx\Delta T_{mov}/T_{mov}$ in numerical experiment, where ΔT_{mov} - a delay

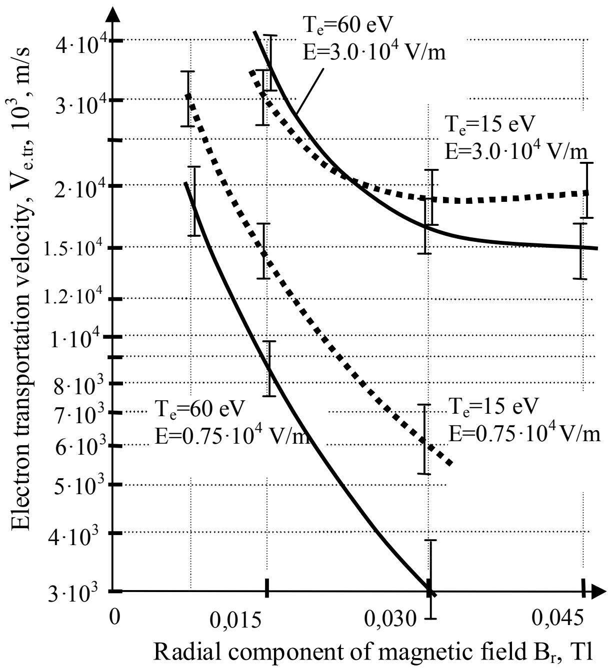

Figure 2. Velocity of electron transportation $V_{e\,tr}$ to the anode across magnetic field B_r because of dispersion in area of azimuthal heterogeneity of ion concentration $\Delta n_i/n_i$=0.01.

because of electron scattering $\Delta T_{mov}=T_{mov}(\Delta\varphi\neq 0)-T_{mov}(\Delta\varphi=0)$. If it appeared that $\Delta n_e/n_e<\Delta n_i/n_i$ when $\Delta\varphi$ increased and the second experiment was carried out and so on until $\Delta n_e/n_e\geq\Delta n_i/n_i$ become thru and corresponding $V_{e.tr}$ (at $\Delta\varphi$) become the decision of a current task. The ratio $\Delta n_e/n_e\geq\Delta n_i/n_i$ meant that the electron charge compensates a charge of ions in the area of heterogeneity. Then other value H_{int} was retrieved casually of a range (0.1 … 1.5)$\cdot R_{gyro}$ and other series of experiments was carried out to fine out others $V_{e.tr}$ (at $\Delta\varphi$). Among experiments it was chosen that when $\Delta\varphi\rightarrow\Delta\varphi_{min}$. The range date of $\Delta\varphi_{min}$ was 0.5 … 2.5 V. Results $V_{e.tr}(B_r, E, T_e)$, presented in a Fig. 2, 3, 4, have been calculated in this way.

Thus, it was shown that in conditions characteristic for HT operation mode, owing to electron scattering in the area of ion concentration heterogeneity. Electron concentration in this area increases so, that the charge of electron can compensate a charge of ions. By this, because of electron scattering, velocity of electron transportation to the anode $V_{e.tr}$ is close to characteristic value $(3…6)\cdot 10^3$ m/s, calculated on experimental data.

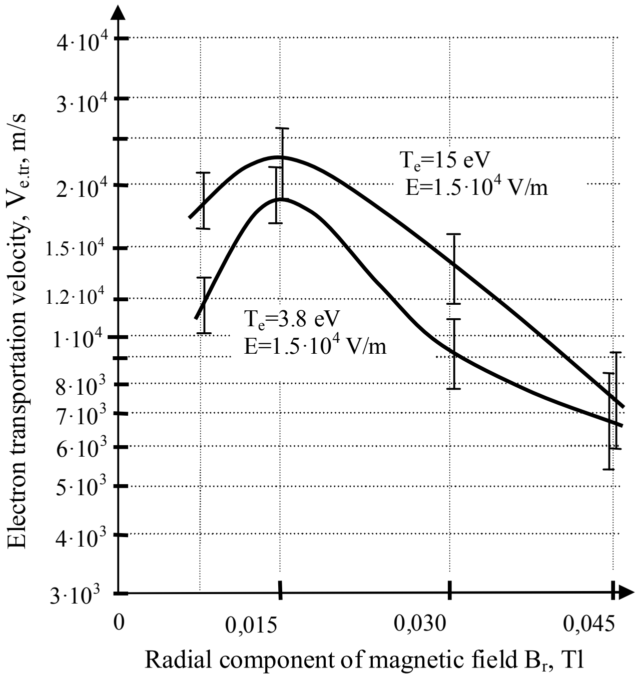

Figure 3. Velocity of electron transportation $V_{e\ tr}$ to the anode across magnetic field B_r because of dispersion in area of azimuthal heterogeneity of ion $\Delta n_i/n_i=0.01$.

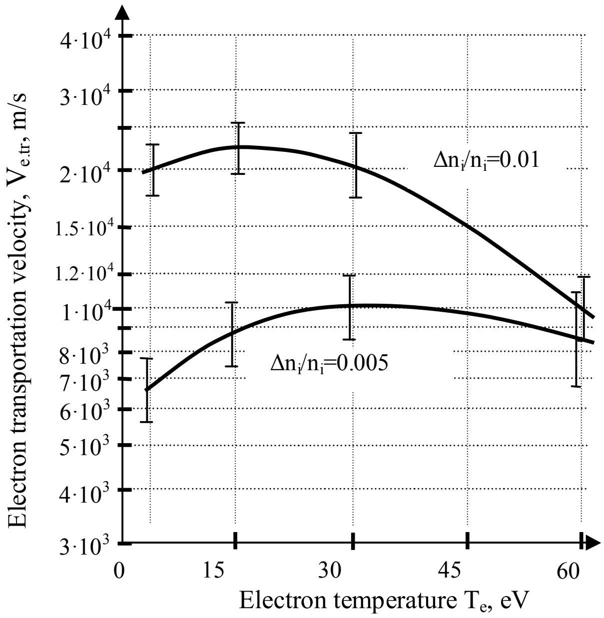

Figure 4. Velocity of electron transportation $V_{e\ tr}$ to the anode across magnetic field B_r because of dispersion in area of azimuthal heterogeneity of ion concentration $\Delta n_i/n_i$ at B_r=0.015 Tl, E=$1.5\cdot 10^4$ V/m depend upon $\Delta n_i/n_i$.

III. Influence of an magnetic field azimuthal component to electron transportation

Possible influence azimuthal component of magnetic field B_φ to velocity of electron transportation (look Fig. 5) and, as consequence, to the value of HT discharge current was studied.

A. Hypothesis on electron cross-field transportation caused by magnetic field azimuthal component

B_φ azimuthal component of magnetic field is generated by HT discharge current, it varies in a direction and value along radius of the discharge chamber and is stationary in time. Also B_φ component can be strengthened artificially. The HT discharge current, including ionic and electronic components as shown in a Fig. 5, generates azimuthal component of magnetic field B_φ of the order of 10^{-5} Tl. It is assumed that azimuthal component of a magnetic field effect (by means of Lorentz's force $F_l=\pm B_\varphi(r)\cdot V_{er}\cdot q$) azimuthal movement of each electron so that at each subsequent scattering (reflection) of electron on a wall (in close to the wall reflecting layer) the place of reflection (a point of reflection) is displaced against an electric field to the anode – electron trajectory of movement is broken off (look Fig. 5). Thus, electrons move to the anode. For this effecting it is essentially important that direction and value of azimuthal component $B_\varphi(r)$ of a magnetic field is varied along radius of the discharge chamber. Influence of Lorentz's force, which is determined by azimuthal component (a variable along radius) of a magnetic field and by radial component (it is suppose as constant in time and space) of an electron velocity V_{er}, increases at movement of electron from an average line to a wall of the discharge chamber. If constant electric field and variable Lorentz's force effect electron, which moves in a radial direction, when the azimuthal trajectory of electron drift deviates the closed trajectory on everyone cycloid coil. Thus, electron moves towards the anode, increasing HT discharge current.

Generating B_φ of an opposite direction, it will interfere with moving of electron along an electric field, reducing discharge current.

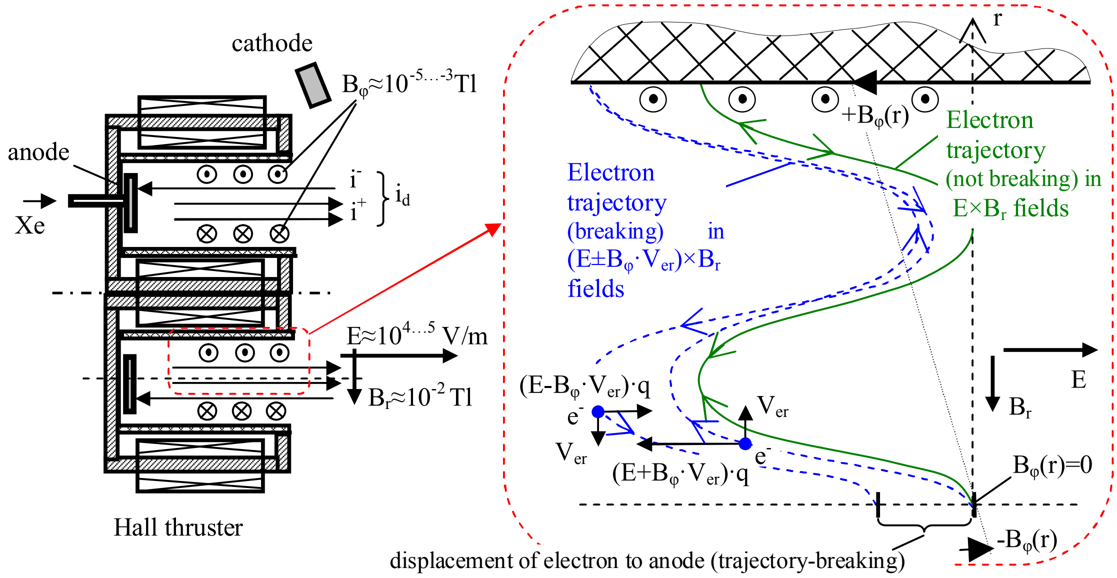

Figure 5. Displacement of electron to anode under influence stationary force of electric field $E\cdot q$ and variable Lorenz force $F_l=\pm B_\varphi(r)\cdot V_{er}\cdot q$.

B. Experiment to reveal magnetic field azimuthal component B_φ influencing to electron cross-field transportation velocity

It is expected, that at the stationary mass flow rate $\dot{m}_a$ and discharge voltage U_d by increasing (or reducing) electron transportation velocity to an anode a discharge current will be change also in the same way. Change of a discharge current will be qualitative confirmation of influence B_φ to electron transportation velocity. To check up possible influence B_φ components to electron transportation velocity and to a discharge current the typical design of the HT accelerator were added by elements (coaxial conductors), to generate demanded B_φ (look Fig. 6). Selecting value and a ratio of currents I_{out} and I_{in} in coaxial conductors, it was received $B_\varphi(r)\approx 1$ mTl of the demanded value and direction. By experiment the discharge was ignite firstly and acceleration operation mode of HT was established. Then additional B_φ component of magnetic field was generated for short-term period and change of a discharge current ΔI_d was registered.

In HT operation mode (look Fig. 6) with Xe mass flow rate $\dot{m}_a$=0.16 mg/s through the discharge chamber with a width b_k=7 mm, U_d=170 V, cathode potential drop $U_c\approx 20$ V, I_d=0.23 A, $B_r\approx 44$ mTl at $B_\varphi(I_{out}=30\text{ A})\approx 1$

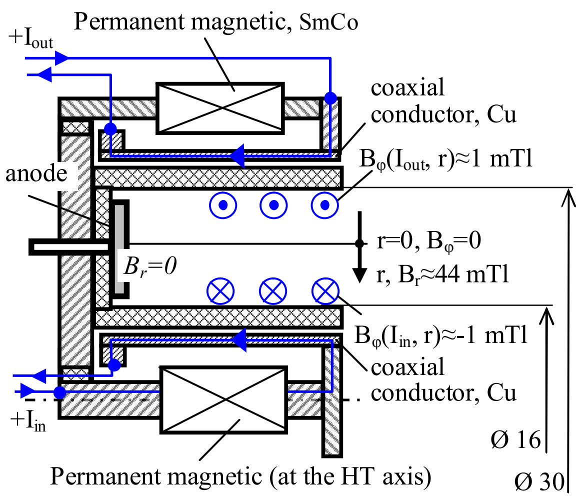

Figure 6. Scheme of experiment with HT: coaxial conductors and currents I_{out} and I_{in} for holding magnetic field component $B_\varphi(r)$ in experiment.

mTl and $B_\varphi(I_{in}=15\ A)\approx-1$ mTl as in a Fig. 6 it has been registered discharge current increasing $\Delta I_d\approx0.003$ A (look Tab. 1), that qualitatively meets to expected growth of transportation velocity $V_{e.tr}$ through a discharge interval and to growth electron components I_e of a discharge current at saturation (constancy) of ion component I_i. While B_φ components were generated of one direction $B_\varphi(I_{out})\approx1$ mTl and $B_\varphi(-I_{in})\approx1$ mTl when the discharge current has not changed $\Delta I_d\approx0$. At $B_\varphi(-I_{out})\approx-1$ mTl and $B_\varphi(-I_{in})\approx1$ mTl it was registered decreasing of a discharge current $\Delta I_d\approx-0.007$ A, that qualitatively meets to expected decreasing of velocity $V_{e.tr}$ and to the decreasing of electron components I_e of a discharge current at the decreasing ion component $I_i\sim I_e$. By HT experiment it is qualitatively confirmed that the discharge current can be changed (to increase or reduce), changing B_φ value and a direction at an external and internal wall of the discharge chamber. Base on results of growth of a discharge current $\Delta I_d\approx0.003$ A we shall estimate growth of $\Delta V_{e.tr}$ as follows. From ratio $I_e/I_i=n_e\cdot V_{e.tr}/n_i\cdot V_i\approx V_{e.tr}/V_i\approx(I_d-I_i)/I_i$ we shall determine $V_{e.tr}\approx(I_d-I_i)/I_i\cdot V_i$. For this purpose velocity V_i of ion with a charge q, weight M_i, which have passed a potential difference $\approx(U_d-U_c)/2$ in discharge chamber, we shall estimate as $V_i\approx(2\cdot q\cdot(U_d-U_c)/2/M_i)^{1/2}$. It is suppose that when ≈90 % of Xe flow are ionized, so that $I_i\approx0.9\cdot I_{ma}=0.9\cdot\dot{m}_a/M_i\cdot q$, when intensity of ionization rate and value of I_i varies slightly by growth components I_e and $I_e=I_d-I_i=I_d-0.9\cdot I_{ma}$. When $\Delta I_d/I_d\approx\Delta I_e/I_e\approx\Delta V_{e.tr}/V_{e.tr}$ and $\Delta V_{e.tr}\approx V_{e.tr}\cdot\Delta I_d/I_d$. Base on date of experiment it was determined $V_i\approx1.1\cdot10^4$ m/s, $I_i\approx0.11$ A, $V_{e.tr}\approx(0.23-0.11)/0.11\cdot1.1\cdot10^4=1.2\cdot10^4$ m/s, and $\Delta V_{e.tr}\approx160$ m/s (look Tab. 1). Value $\Delta V_{e.tr}\approx160$ m/s is estimation of influence B_φ to I_d "from below". Further, we shall compare value $\Delta V_{e.tr}\approx160$ m/s to results of numerical experiment calculation $\Delta V_{e.trC}$.

Table 1. Parameters of HT effected by B_φ

Experiment (look Fig. 6)	1	2	3	4
Direction $B_\varphi(I_{out})$, mTl	⊙, +1	⊗, -1	⊙, +1	⊗, -1
Direction $B_\varphi(I_{in})$, mTl	⊙, +1	⊗, -1	⊗, -1	⊙, +1
$I_{d0}=0.23$ A, $B_r\approx44$ mTl, $U_d=170$ V, $\dot{m}_a=0.16$ mg/s, $B_\varphi(I_{out}=30\ A)\approx1$ mTl, $B_\varphi(I_{in}=15\ A)\approx1$ mTl				
ΔI_d, A	0	0	0.003	-0.007
I_d, A	I_{d0}	I_{d0}	$I_{d0}+\Delta I_d$	$I_{d0}+\Delta I_d$
$\Delta V_{e.tr}$, m/s on experimental date	0	0	160	-370
$\Delta V_{e.trC}$, m/s calculation (look below, item **C.**)	0	0	550	-550

C. Numerical experiment to determine average electron transportation velocity $V_{e.tr}$ to the anode

To determine dependence of an average electron transportation velocity $V_{e.tr}$ to the anode across magnetic field B_r on values B_r, T_e and HT design features it have been curried out following numerical experiment. In the HT discharge interval it have been set following values of fields, energies and the sizes: $E\approx10^4$ V/m, $B_\varphi\approx10^{-5\ldots-3}$ Tl, $T_e\approx5\ \ldots\ 50$ eV, $B_r\approx(15\ \ldots\ 45)\cdot10^{-3}$ Tl, $b_k\approx7.5\ \ldots\ 30$ mm. In this area from plane SS 10^5 electrons with starting velocity chosen from velocity phase space of Maxwell distribution (look Fig. 7) were consistently "emitted". When the i^{th} particle passed the fixed way (2…3) $\cdot b_k$ the distance Δx_i from a plane SS and time $\Delta\tau_i$ of i^{th} particle movement were registered, and average transportation velocity of each i^{th} particle $v_{tri}=\Delta x_i/\Delta\tau_i$ was determined. Then average transportation velocity of all particles $V_{e.trN}=(w_1\cdot v_{tr1}+\ldots+w_i\cdot v_{tri})/(w_1+\ldots+w_i)$ in view of a range of velocity $(v_{ei}+\Delta v_e)$ and statistical weight $w_i=f(v_{ei}, T_e)\cdot\Delta v_e$ of each particle in velocity phase space of Maxwell distribution with density $f(v_e, T_e)$ was determined. Results are plotted in a Fig. 8, 9, 10. It is necessary to notice, that according to the assumption, the electric field influences to $V_{e.tr}$ indirectly - by means of electron temperature T_e.

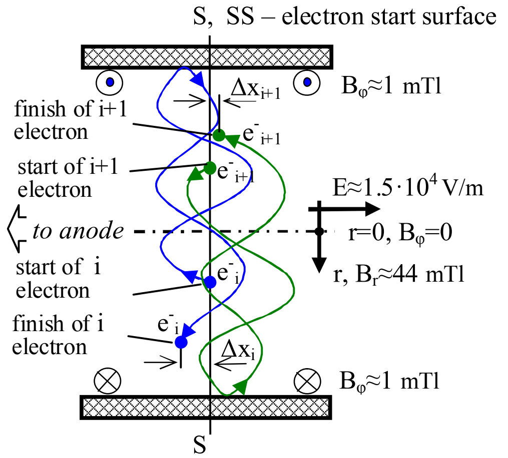

Figure 7. Scheme of numerical experiment. Particles registering for determining of electron transportation velocity $V_{e.trN}$.

Base on analysis of electron movement features under influence of B_φ component it is offered analytical dependence $V_{e.trC}(B_\varphi, B_r, b_k, T_e)$ for approximate calculation

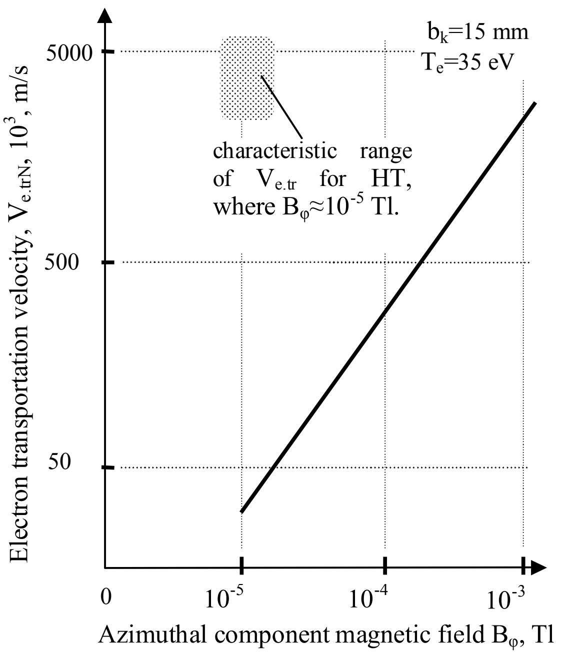

Figure 8. Results of numerical experiment: dependence of electron transportation velocity $V_{e.trN}$ on an azimuthal component B_φ of magnetic field.

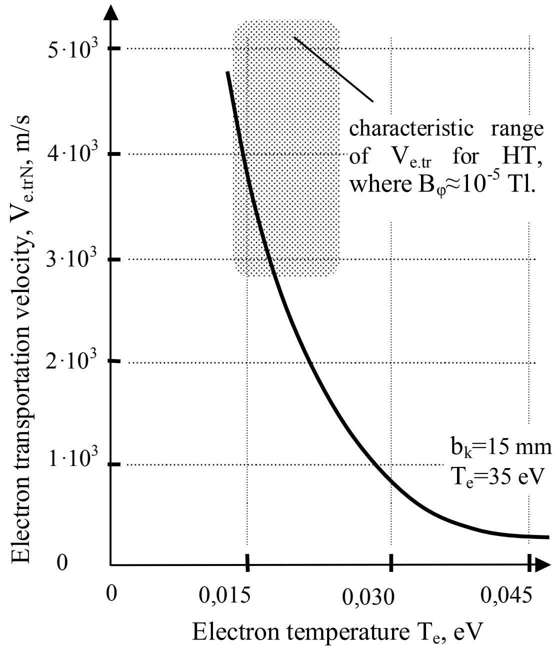

Figure 9. Results of numerical experiment: dependence of electron transportation velocity $V_{e.trN}$ (under influence of an azimuthal magnetic field $B_\varphi=10^{-3}$ Tl) on radial component B_r.

$$V_{e.trC} = \frac{B_\varphi \cdot T_e}{4 \cdot b_k \cdot B_r} \qquad (1),$$

where: B_φ, B_r - azimuthal and radial magnetic field components; T_e - electron temperature; b_k - width of the HT discharge chamber.

Base on the date of experiment: discharge voltage U_d=170 V, cathode potential drop $U_c \approx 20$ V, $B_r \approx 44$ mTl, $B_\varphi \approx 1$ mTl, b_k=7 mm the value $\Delta V_{e.trC}$ was calculated as $\Delta V_{e.trC}=V_{e.trC}$, assuming that there are no other ways of electron transportation. For this discharge conditions the temperature T_e in discharge chamber was roughly estimated base on its value at the discharge chamber entrance as follows $T_e \approx 2/5 \cdot (U_d-U_c)/2=30$ eV following equation (4) – balance of energy flow [2], assuming that outside the discharge chamber potential drop $\approx (U_d-U_c)/2$ is concentrated and there is not electron energy losses outside the discharge chamber. Then value $\Delta V_{e.trC} \approx 550$ m/s was calculated on equation (1). The value $\Delta V_{e.tr} \approx 160$ m/s, calculated base on data of experiment (look Tab. 1), has appeared in 4 times less one, calculated theoretically $\Delta V_{e.trC} \approx 550$ m/s. The reason of this, first of all, that in experiment the configuration of B_φ component distribution was irregular because of uniform distribution of currents I_{out} and I_{in} (which generate B_φ component) along an azimuth of coaxial conductors.

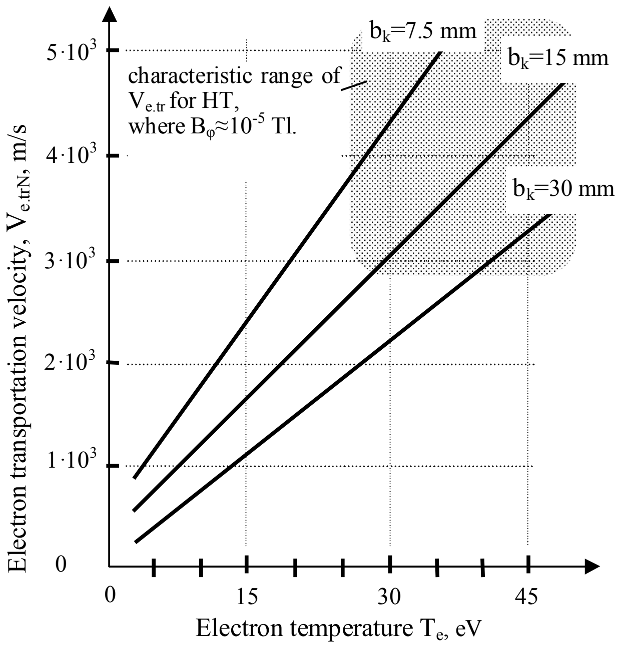

Figure 10. Results of numerical experiment: dependence of electron transportation velocity $V_{e.trN}$ (under influence of azimuthal magnetic field $B_\varphi=10^{-3}$ Tl) on electron temperature T_e at various width of discharge chamber b_k at B_r.=15 mTl.

IV. Influence of local pulsing electric field to electron transportation

Now there is no final and noncontradictory explanation of how an impulse exchange of electrons and electrons maxwellization is occurs in HT plasma. Electron-electron, electron-ion or electron-atom collisions are not effective enough for maxwellization.

A. Hypothesis on local pulsing electric field and electron maxwellization and also cross-field transportation caused by it

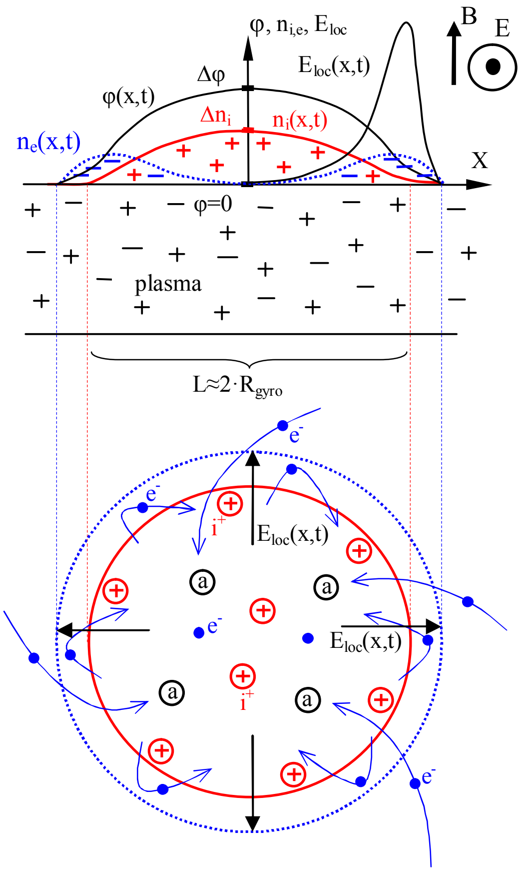

Figure 11. Particles concentration distribution: "motionless" ions $n_i(x)$ and inphase oscillating electrons $n_e(x, t)$ in HT plasma during oscillation when t=0, $\Delta\varphi \to max$.

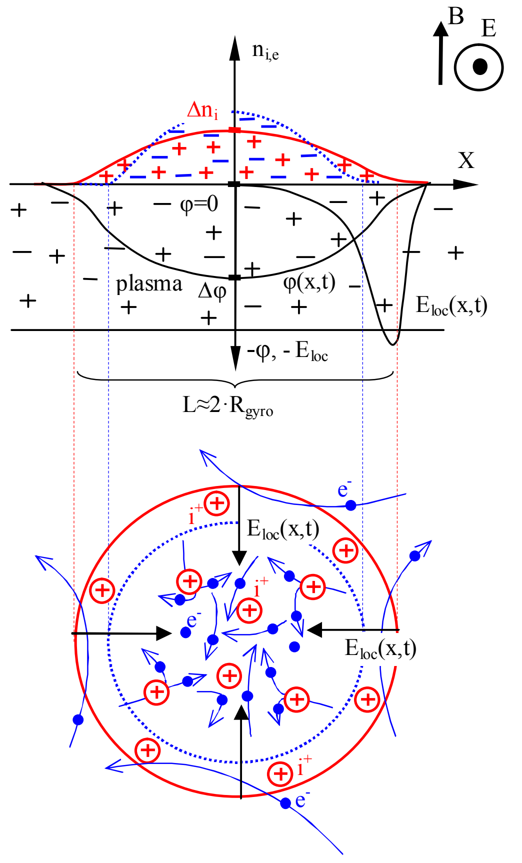

Figure 12. Particles concentration distribution: "motionless" ions $n_i(x)$ and inphase oscillating electrons $n_e(x, t)$ in HT plasma during oscillation when t=T/2, $\Delta\varphi \to min$.

In these researches it is assumed that in conditions of HT plasma it is possible existence of local areas (look Fig. 11, 12) extent of the order of electron gyro-radius R_{gyro}, in which there is an electric field (central-symmetric, pulsing with frequency *f=1 ... 3 GHz* and potential drop of the order of electron temperature or less). Scattering of electrons at movement through these local areas (when electron velocity V_e and energy are varied) can be the mechanism of electron maxwellization. Besides scattering of electrons breaks it closed drift trajectory and can cause electron transportation to the anode with some average velocity $V_{e.tr}$. Let's notice that researches [3], in which characteristic fluctuations with frequency of 1…3 GHz were registered, are known. We suppose that existence of such local areas can be supported owing to cyclicity ionization process within space of this area as follows.

During the casual time moment in some conditionally allocated plasma area a concentration of electron with energy more threshold (30 eV for some ceramic materials) can quickly increase, for example, by restoration of potential drop (in close to the wall layer) after its falling up to zero because of inrush effect of secondary electron emission in charge-saturation regime. Then in this conditionally allocated plasma area of the extent of gyro-radius

R_{gyro}≈0.001 m concentration of ions and electrons will simultaneously increase owing to ionization of atoms by primary electrons for the period of the order $\tau_i \approx R_{gyro}/V_e \approx 0.3\cdot10^{-9}$ s ($f \approx 1/\tau_i \approx 3\cdot10^{9}$ Hz), during which these primary electrons pass this area. After ionization just born electrons and primary electrons dissipate chaotically and moves (simultaneously for the period of the order τ_i) from the center of allocated area, in which there is a unbalanced charge of slowly moving ions. If concentration of atoms is of the order $10^{19\ldots20}$ m^{-3} the charge of ions with concentration $10^{14\ldots15}$ m^{-3} and primary potential drop 1…10 V, and also a local central-symmetric electric field $E_{loc}=\Delta\varphi/R_{gyro}\approx10^{3}$ V/m are resulted. This E_{loc} field hold and then carries back to the center of local area a part of electrons (enough slow). During this period electrons from plasma outside of local area synchronously with electrons, which have been trapped earlier, also carries in this local area (are focused in its center) by a field E_{loc} and ionize atoms. As a result near to the center the superfluous negative charge is concentrated, and near to edge of area it is concentrated a superfluous positive charges that create potential drop $\Delta\varphi$ and a field $E_{loc}\approx-\Delta\varphi/R_{gyro}$. Than superfluous negative charge is concentrated near to the center a part of electrons, moving from outside plasma in local area, dissipate by a field E_{loc} and flow round this area. These flowed round electrons not participate in ionization and not break synchronism of collective movement of trapped earlier electrons and just born electrons in direction center-periphery of local area. Electrons leave (for the period of the order τ_i) from the center of area, in which an unbalanced charge of ions arises and a potential drop $\Delta\varphi$ is generated - cyclic process is repeated. With each new cycle potential drop $\Delta\varphi$ and a field E_{loc} will increase in local area because of accumulation of ions and electrons in it, which are trapped by a field E_{loc} up to value $\Delta\varphi\approx(T_e-\varphi_i)/(1.5 \ldots 2.5)$.

It is supposed that energy to maintain the periodic oscillatory process of division of charges in such local area is transferred from external plasma with "hotter" primary electrons to local area with "colder" electrons through process of ionization of atoms. By process of atom ionization energy from primary electrons is divided between tow new electrons, which are trapped by a local electric field E_{loc} and participate in periodic collective movement in a direction the center-periphery. It is expected that in such area because of the increased concentration of electrons, which are trapped by a superfluous charge of ions, ionization of atoms can be more intensive. Further because of "burning out" of atoms in such local area it will be disturbed conditions of supporting of periodic ionization, which supplied oscillatory process by energy, and because of dispersion of energy a pulsation of an electric field E_{loc} will damp until concentration of atoms will not increase.

It is supposed that similar processes can occur both in the field of atom ionization and in the field of ion acceleration where concentration of atoms is less in tens times.

B. Numerical experiment on electron maxwellization and cross-field transportation caused by local pulsing electric field

Base on the assumption about existence of local areas by extent of the order gyro-radius R_{gyro} with a pulsing electric field E_{loc} it was curried out numerical experiment and function of electron distribution on energies, drifting in crossed magnetic and electric fields (look Fig. 13) similarly to [4] is determined. In these researches by numerical experiment it was established the average disbalance of energy of electrons passing through local area with a pulsing electric field E_{loc}. At the temperature T_e=40…50 eV and $E_{loc}=10^{3\ldots4}$ V/m disbalance of energy less 0.3 eV. Thus, the exchange of energy is very few and also energy of electrons (participated in collective oscillatory process in local area) also remains close to a constant. In this researches it is not investigated possible disturbance of phase synchronism of an electron charge periodic movement because of interaction with electrons passing through local area with a E_{loc}. Velocity $V_{e.tr}$ of electron transportation along an electric field across to a radial magnetic field as result of individual acts of electron scattering under the

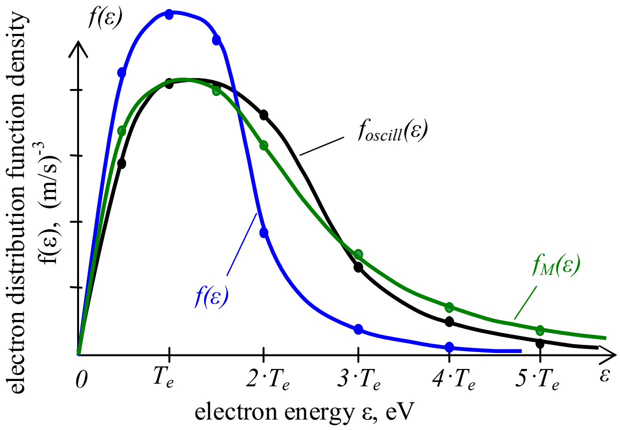

Figure 13. Distribution function density f(ε) of electron drifting in crossed E×B fields then its initial energy is 40 eV, B_r=15 mTl, E=300 V/cm.

$f_{oscill}(\varepsilon)$ – Density of the electron distribution function on energy (DEDFE) determined in numerical experiment than plasma oscillations take into account.

$f(\varepsilon)$ – DEDFE determined in numerical experiment without plasma oscillations.

$f_M(\varepsilon)$ – DEDFE at Maxwell distribution T_e=56 eV.

pulsing field E_{loc} was determined in experiment also. Base on analyzing of results follows conclusion have been made: electron distribution function, formed under influence of pulsing local electric fields, is close to Maxwell distribution. Base on results of numerical experiment dependence of electron transportation velocity to anode $V_{e.tr}(B_r)$ was plotted at values fields E, B_r and temperature T_e, which are characteristic for HT (look Fig. 14). Value $V_{e.tr}$ has appeared much less than real transportation velocity $(3…6)\cdot 10^3$ m/s, which can be calculated base on experimental date of HT operation mode.

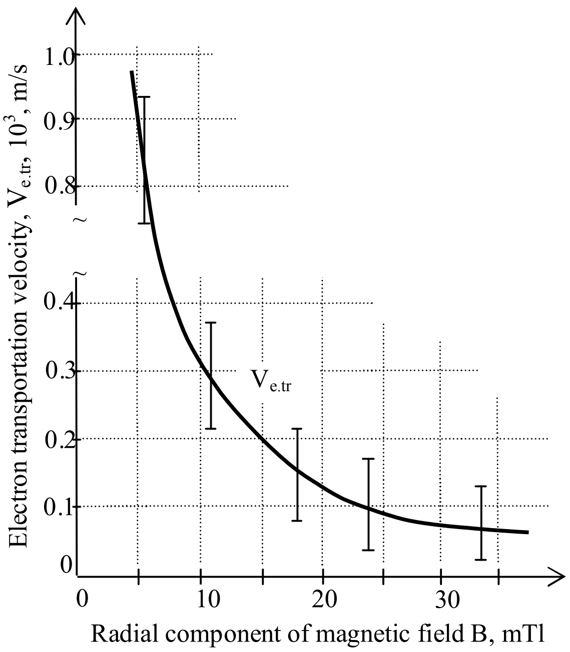

Figure 14. Electron transportation velocity $V_{e.tr}$ in plasma along electric field $E=10^4$ V/m across radial magnetic field B_r under influence of fluctuations of an electric field in local areas of plasma heterogeneity at T_e=15 eV.

V. Conclusion

Analysis of numerical calculations and experimental researches are resulted as follows.

It was shown by numerical experiment that in HT operating mode electron scattering in the area of ion concentration azimuthal heterogeneity $\Delta n_i/n_i<1$ % of the extent of the order 10^{-2} m can cause transportation of electrons to the anode with characteristic velocity of the order $10^3…10^4$ m/s.

Effecting HT discharge current value of magnetic field azimuthal components B_φ has been qualitatively confirmed in experiment at the HT operation when this component B_φ has been strengthened tens times. Influence of magnetic field azimuthal component B_φ of the order $\sim 10^{-5}$ Tl (self-generated only by own discharge current) to electron movement can not provide (explain) anomalous electron transportation velocity across radial component (strongest, about 15 mTl and more) magnetic field along electric field, which is observed in characteristic HT operation mode. It was shown in numerical experiment that it is possible influence electron transportation velocity (changes of the order $10^3…10^4$ m/s) across a radial magnetic field by increasing artificially of an azimuthal component B_φ magnetic field up to 1 mTl.

Plasma potential fluctuations of frequency of the order 1…3 GHz, which were registered earlier by other researchers, can be consequence of periodic movement of a charge (electrons) in local plasma arias of the extent of electron gyro-radius. Owing to intensive interaction with electrons this potential fluctuations can cause electron maxwellization in plasma. Also scattering of electrons in these areas can couse electron transportation across magnetic field (changes of the order $10^2…10^3$ m/s) but do not play the basic role in plasma conductivity.

It is planned to continue researches of an regularities of the self-consistent local stationary electric field in the area (extent $\sim 10^{-2}$ m) of azimuthal heterogeneity of ions and pulsing electric field in the area of the extent of electron gyro-radius.

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