Low-frequency wave experimental investigations, transport and heating of electrons in stationary plasma thruster SPT.

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Abstract: Studies oscillations of plasma potential, electron temperature and ion current in SPT channel showed that these oscillations represent waves which extend the azimuth and along the channel. At frequencies f <80 kHz oscillations change synchronously. Oscillations propagate as a azimuthal wave k_φ for f> 80 kHz. Phase velocity $c_{\varphi p}$ coincides with the direction of electron drift velocity u_e. It increases linearly from $1.3 \cdot 10^6$cm/s to $2.4 \cdot 10^6$ cm/s with changing the discharge voltage in limit (170-350)V, remains almost constant with changing Hr more than doubled and is independent of frequency up to 1MHz (no dispersion). Longitudinal wave vector k_z coincides with the direction of ion movement v_{iz}. Phase velocity of longitudinal waves c_{zi} for oscillations of ion current J_{zi} and plasma potential s_{zp} are different. The phase velocity c_{zp} is more in 2 times than c_{zi}. Longitudinal oscillations of plasma potential are observed at f> 400 kHz but longitudinal oscillations of ion current observed beginning at f> 80kHz. It is shown that the ion density modulation in the channel is directly related with oscillations of plasma potential and electron temperature to result from the change of the ionization rate, and the appearance of ion azimuthal velocity component. This made it possible to prove that the transport of electrons along the channel is carried out precisely due to the drift in the azimuthal electric field and radial magnetic field. The high correlation between oscillations of the electric field and of plasma density realized precisely due the ionization process. It is shown that the source of electron heating is the interaction of the oscillations drift electron current with the wave azimuthal component of the plasma potential. In this case, the perturbation velocity of the electrons in the azimuthal direction (drift velocity) is determined by longitudinal wave of the plasma potential.

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Hr = radial component of magnetic field
Je = longitudinal component of electron current
$\tilde{n}_p$ = oscillations amplitude of plasma density
n_p = direct component of plasma density
S = channel section
T = oscillation period
f = oscillation frequency
ω_H = electron cyclotron frequencies
n = wave number
u_H = electron drift velocity
c = light velocity
c_i = wave phase velocity
z, = coordinate in direction along channel
φ = coordinates in direction azimuth channel
H_o = maximum value of radial component of magnetic field
U_p = plasma potential
T_e = electron temperature oscillation
k_Z,, = longitudinal components of wave vector
k_φ = azimuthal components of wave vector
c_{pz} = phase velocity longitudinal components of plasma potential oscillation
$c_{p\varphi}$ = phase velocity azimuthal components of plasma potential oscillation
c_{iz} = phase velocity longitudinal components of ion current oscillation
$c_{i\varphi}$ = phase velocity azimuthal components of ion current oscillation
J_i = direct ion current along channel
$\hat{J}_i$ = alternating ion current along channel
σ_{i0} = electron-neutral elastic collision section
σ_i = ionization section
I = ionization potential
E_0 = electric field strength
Q = ionization velocity
v_{pz} = longitudinal components plasma potential
$v_{p\varphi}$ = azimuth components plasma potential
$v_{i\varphi}$ = azimuth components ion velocity
v_{iz} = longitudinal components ion velocity
U_d = discharge voltage
z_0, R = length and average radius of channel
$\Delta\varphi$ = phase shift
J_H = Hall current
K = correlation coefficient between oscillations of plasma density and electrical field
N = neutral density
β = Hall parameter
σ = conductivity
v = temperature electron velocity
τ = electron-neutral collision time
J_d = discharge current
u_e = electron transport velocity along channel
E_φ = electrical field azimuthal component

Although the study of SPT goes on over 40 years, there are several physical phenomena, which define the operation of the thruster, but are not fully understood. This primarily concerns the mechanisms describing diffusion and heating of electrons in the thruster channel.[1-3] Obviously these processes have a major importance both for the formation of electric field and for the ionization of the working propellant in the SPT. Under condition magnetized electrons, only collisions of these with neutrals and ions do not explain electron current passing along the channel.

In the channel observed azimuthal wave of electric field E_φ and oscillations of plasma density n_p. Electrons, drifting in a radial magnetic field of H_r, can move across the magnetic field. Longitudinal electron current J_e, which arises in this case, can be substantially more if there is a fairly high correlation between by oscillations plasma density n and by electric field strength E_φ.

$J_e = ec\int < E_\varphi \tilde{n}_p > dS / H_r$ where $< E_\varphi \tilde{n}_p > = 1/T\int_0^T E_\varphi \tilde{n}_p dt$ denote $K = < E_\varphi \tilde{n}_p > / E_{\varphi 0}\tilde{n}_{p0}$

*E*xperiments presented in[2] show that in the channel of thruster are appearing significant on amplitude azimuthally asymmetric potential oscillations and oscillations of plasma density in the frequency range f = 20-100 kHz, the correlation between these reaches K = 0.15-0.3 for SPT in which the magnetic field increases from the anode to the cathode. Changing the configuration of the magnetic field, in which increases the electron current, also increases the value of K. The estimates of the electron current for different configurations of magnetic fields are consistent with a reasonable accuracy of 30% with the experimental results. It should be noted that increasing the electron current through such a mechanism is not accompanied by electron heating. There is an assumption that via plasma turbulence the transfer of energy is realizing along the spectrum of frequencies from low frequency oscillation 20-40kHz. The dissipation of energy occurs at frequencies close to electron cyclotron frequencies ω_H. Experimental studies, published in,[5] devoted to studying the effect of high (turbulent) fluctuations ((5-10) MHz on the diffusion of electrons, have shown, that the effective collision frequency is increased but not sufficiently many to explain the magnitude of the electron current flowing along the channel in the region where the magnetic field has a maximum value.

Recently, a series of investigation that are experimental[6] and uses numerical models[7-8] for the study the azimuthally asymmetric oscillations and the influence of such oscillations, on the transfer of electrons across the magnetic field and electron heating have been published. Analysis of plasma stability in the thruster channel, having specific dimensions, configuration of the magnetic field, under certain operating parameters (discharge voltage, flow rate of propellant), have been accomplished. The interaction of the electric field with plasma components is considered. This allows comparing experimental results with numerical calculations.

In work[7] investigated the development of purely azimuthal waves in linear and nonlinear approximation. Main unstable mode, which develops in the channel, is the wave with number n = 3. Phase velocity $c_i = 2.7 * 10^3$ m/s is comparable with ion-acoustic velocity. The main mechanism, that limits the amplitude of the azimuthal wave, is the interaction of electrons drifting in the fields E_φ, H_r, with this wave. Estimations have shown that such interaction decreases the drift velocity $u_H = cE_\varphi/H_r$ on order. The authors note that one of the key points, influencing on electron transport is the gradient of electron pressure and associated temperature oscillations of the electrons.

In[8] to describe the anomalous diffusion of electrons was investigated two models. In the hybrid model, electrons are considered to be liquid, the remaining components of the plasma - particle. In the three fluid models all the components of plasma are considered as particles.

Both of these models show that in the channel should appear oblique waves propagating in the longitudinal and azimuthal directions. Wavelengths in the azimuthal direction are approximately equal to 5 cm, but the phase velocity c_i and frequency are very different. Calculations show that in the channel is $c_i = 4{\cdot}10^3$m/s, and $f \approx$ 40kHz for the hybrid model, and $c_i = 3{\cdot}10^7$m/s and $f \approx$ 5MHz for the fluid model. Despite this difference, the calculated electron diffusion for these models is comparable and agrees qualitatively with the experimental results.

Analysis of studies shows that there are now several models that differ markedly in describing the mechanisms of electron diffusion in the channel of SPT, but the calculation results agree qualitatively with the experimental results.

Experimental setup and measurement techniques.

The measurements were carried on a laboratory model of stationary plasma thruster SPT-70, in RRC "Kurchatov Institute". The scheme of SPT shown in Fig 1a, the radial component magnetic field along channel is in Fig. 1b.
The channel was made of an insulator brand ANB. The dimensions of the channel are the outer diameter- 72 mm, inner 40mm, the distance from anode to exit 37mm. Vacuum equipment allowed to work under pressure $(1\text{-}2){\cdot}10^{-4}$ Torr (air). In the vacuum facility was the transporter, which allowed moving the probes in three directions. The main results were obtained on Kr for flow rate 1.7mg/s, in the range of discharge voltages 150-400V.
Measurements were made in operation at the optimum magnetic field $H_o \approx 0.01\text{-}0.012$T, when the discharge current was minimum. During the experiments were measured the plasma parameters inside the accelerating channel and at the exit.

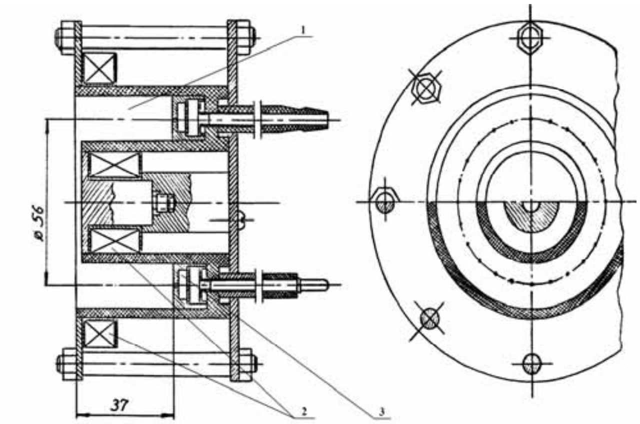

Figure 1a. The scheme of plasma thruster SPT-70
(1- accelerating channel, 2- magnet coils, 3-anode)

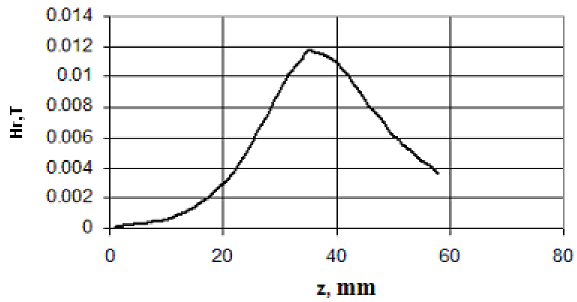

Figure 1b. The radial component magnetic field in channel SPT.

Measurements of plasma potential were carried out by using the hot (emissive) probes. Scheme of the probe is shown in Fig. 2.

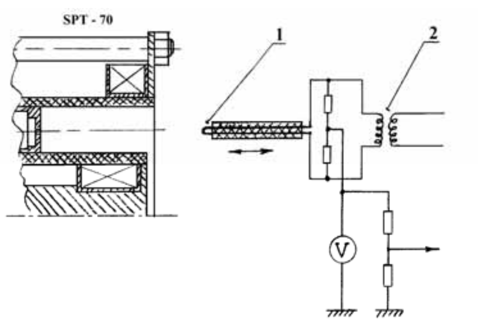

Figure 2. Scheme for measuring the plasma potential, using a hot probe.
1-probe, 2- isolating transformer

The probe has been made in the form of a loop of tungsten wire with radius of 1.5mm. Heating of probe has been realized through an isolating transformer 2. For measurement of the ionic currents the probes were used, in which collectors were made of tungsten wire in diameter 0.5mm and a length 1mm. Single probe allowed to measure distribution of plasma paramrters along and across the channel and the ratio between constant and variable components. Structure of the oscillations has been studied with the help of two probes. In this case, one probe was basic and another could be moved relatively of it both along azimuth and along the channal. In addition for measuring plasma parameters in the outer wall of the discharge chamber were made holes in which were placed probes. These probes were located along the accelerating channel from the anode to the exit and in three sections along the azimuth. Signals of probes were recorded by a digital oscilloscope.

To determine the phase shifts we used two methods. By using filters, oscillations harmonics of the plasma potential and ion current extracted and phase shifts between which analyzed. Another technique was the following, oscillations, obtained with the two probes, expanded in a Fourier series. This allowed us to have a set of harmonics that contain information about amplitude and phase of harmonics. Comparison phases of harmonics, obtained with different probes, made it possible to determine the phase shifts. Comparing results obtained by using these techniques has shown that these results are similar.

Wave properties of plasma potential and electron temperature oscillations.

Studies carried out by hot and cold probes, performed ealier[11,12] and now, revealed that in the channel and near the exit observed plasma potential oscillations V_p and these are identical oscillations of electron temperature T_e. Near the anode plasma potential oscillations are synchronized. Starting with z = 1.5-2cm plasma potential oscillations for f~ 60-1000kHz are the wave, which extends on length k_Z, and on am azimuth k_φ of channel. Oscillations in the frequency range f <60 kHz synchronous over the entire length of channel. The largest relative oscillation amplitude observed at the exit, where it reaches 30-40%.

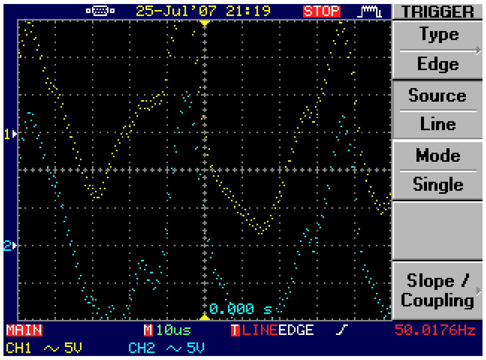

Figure 3. Oscillograms of oscillations of the plasma potential at exit of channel.

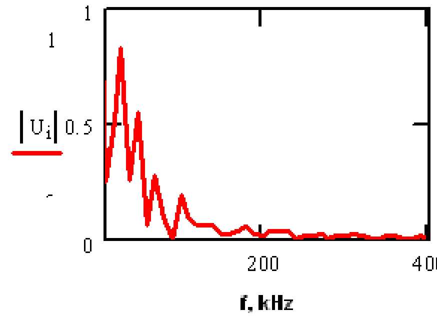

Figure 4a. The spectral composition of the oscillations in the frequency range f = 10-400 kGz.

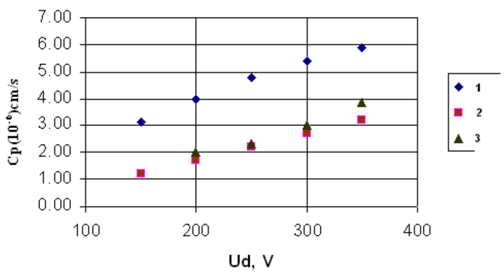

Figure 5. The dependence of the component of the phase velocity on the discharge voltage *(1-longitudinal wave, 2.3-azimuthal wave)*

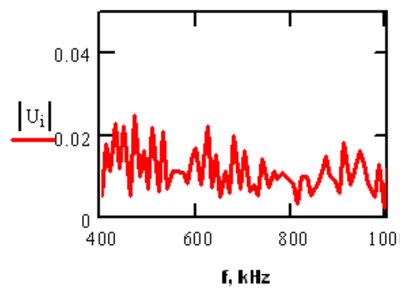

Figure 4b. The spectral composition of the oscillations in the frequency range f = 400 - 1000 kGz

That azimuthal wave of plasma potential are generated into channel, is confirmated the appearance the azimuthal component of ion velocity, which have different value.[10] On Fig. 3, 4a, 4b shows oscillograms of plasma potential U_p and spectral composition these oscillations $|U_i|$. The largest amplitude of synchronous oscillations of the plasma potential is observed at frequencies f = 30-60kHz. The maximum amplitude azimuthal waves observed at frequencies 70-120kHz. In the region f> 400kHz oscillations amplitude decreases slowly with frequency.

Measurements components phase velocities of the potential oscillations are shown in Fig. 5. These linearly increased with discharge voltage. The phase velocity of the azimuthal component of the wave varies in the range (1-2.7)10^6cm/s, while the phase velocity of longitudinal waves is (2-5.5)10^6cm/s for discharge voltage 100-350V. Velocity $c_{p\varphi}$ does not depend on the frequency harmonics f> 80kHz (not observed dispersion), velocity c_{pz} does not depend on the frequency harmonics f> 400kHz but for the frequency f <400kHz it rapidly increases. Both components are not changed by magnetic field H_0 in limit variation it in two times.

Experimental study of the structure of the ion current oscillations.

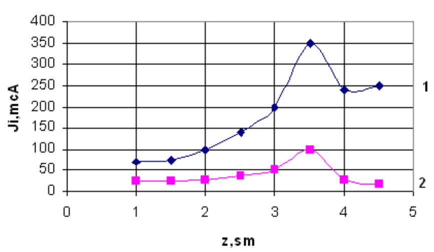

Figure 6. The dependence of direct and amplitude of alternating components of the ion current along the channel. *1- J_i (z), 2- $\hat{J}_j$*

On Fig 6 are shown the change of constant components J_i *(z)* and amplitude of alternating of the longitudinal $\hat{J}_j$ ion current along channel. Dependence of $J_i(z)$ has standard view. Attention is called to change the oscillations amplitude of the ion current along the channel. Functionally J_i and $\hat{J}_j$ dependencies are similar, but relative level of $\hat{J}_i$ / J_i oscillations monotonically decreases to the exit channel. On Fig. 7a 7b shown ion current oscillations, measured in different sections along the channel, and the spectrums obtained by Fourier series expansion. It is seen that they differ both in amplitude and on frequency spectrum. The frequency spectrum (Fig 8a, 8b) can be divided into three band of up to 50kHz, 50-500 kHz, 500-1000kHz.

The largest amplitude is observed in the low-frequency band f = 10-20 kHz over the entire length of the channel.

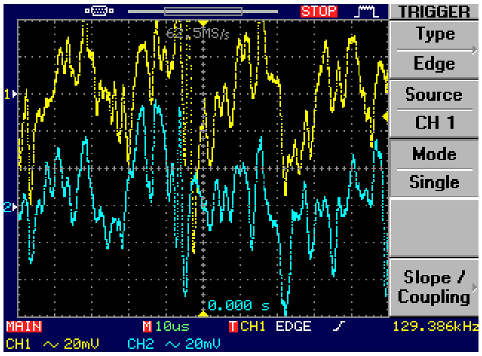

Figure 7a. Oscillograms of oscillation ion current ***z*=3.7sm**

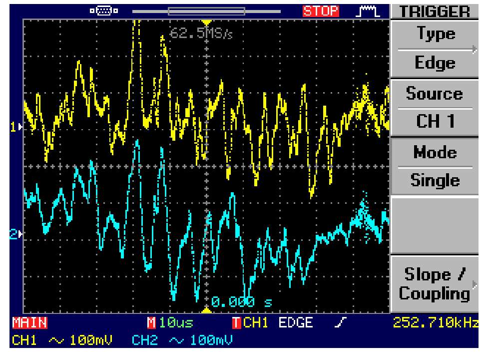

Figure 7b. Oscillograms of oscillation ion current ***z*=3.2sm**

Maximal amplitude occurs at multiples frequencies 50, 60.70 kHz in the frequency band 50-500 kHz. The relative amplitude of high- frequency harmonics increases from the anode to exit. Near of exit the amplitude decreases with frequency for band 50-500kGz then increases for band 300-400kHz, for 500-1000kHz it decreases in several times for f = 1000 kHz. In the middle of channel and closer to the anode, amplitude decreases about ten times for $f \approx$ 500kHz and a little decreases from $f \approx$ 500 kHz up to $f \approx$1000 kHz.

On Fig. 8 shown the values of azimuthal component phase velocity wave $c_{i\varphi}$, which were obtaine in different sections of the channel. Oscillation propagate as wave for f> 80kHz. The direction velocity $c_{i\varphi}$ coincides with the direction of electron drift velocity. It is seen that velocity $c_{i\varphi}$, depends little on frequency and

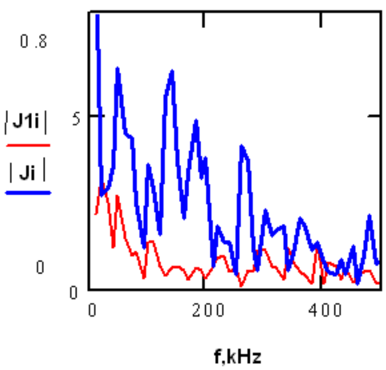

Figure 7c. The spectral composition of the low-frequency harmonic of the ion current
J1i - z = 3.2sm, *Ji - z* = 3.7sm

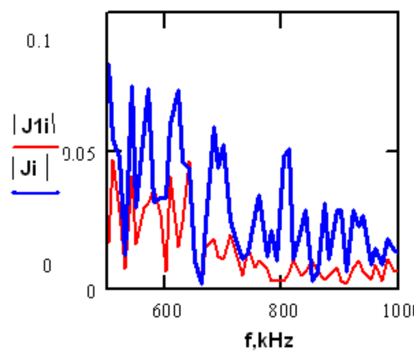

Figure 7d. The spectral composition of the high-frequency harmonic of the ion current
J1i - z = 0.5, *Ji - z* = 0

$c_{i\varphi} \approx 1.6{\cdot}10^6$ cm/s for the 200V discharge voltage (Fig 8a). On Fig. 8b shown $c_{i\varphi}$ dependence on the discharge voltage. It is seen that $c_{i\varphi}$ the phase velocity within limits of the discharge voltage 170-350V increases linearly from $1.2{\cdot}10^6$ cm/s to $2.2{\cdot}10^6$ cm/s.

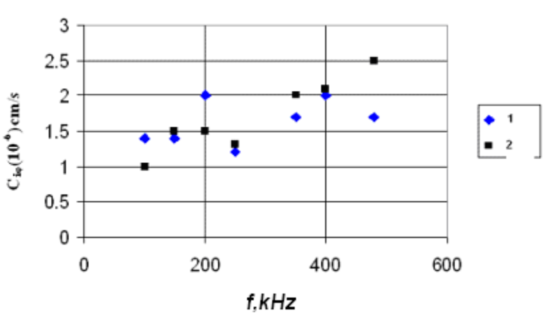

Figure 8a. Dependence of the azimuthal velocity wave $c_{i\varphi}$ on harmonic frequency f
(1-*z*= 3.5cm, 2- *z*=1.2cm)

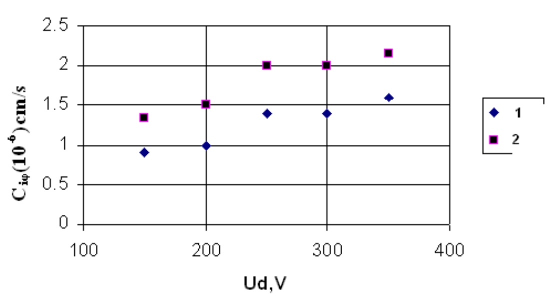

Figure.8b. Dependence of the azimuthal velocity wave $c_{i\varphi}$ on on discharge voltage
(1-*z*= 3.5cm, 2- *z*=1.2cm)

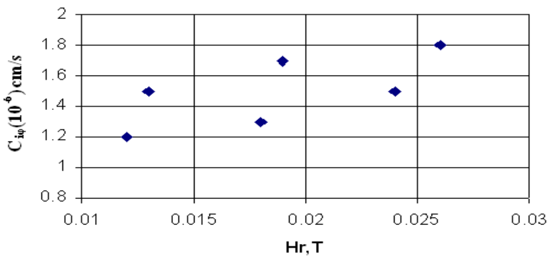

Figure 8c. Dependence of azimuthal velocity wave $c_{i\varphi}$ on magnetic field.

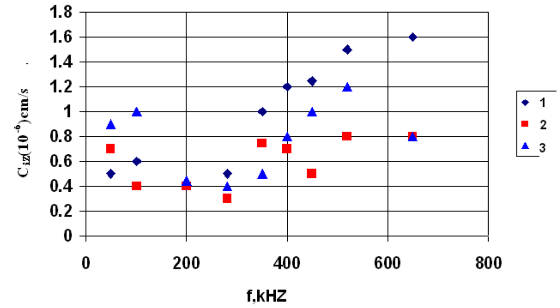

Figure 9. Dependence of along velocity wave c_{iz} on frequency *f*.

(1-z=1.5sm, 2-z =2.3sm, 3- z=3.5sm).

The scatter of the points lies within 30%. The dependence of $c_{i\varphi}$ on the radial component of magnetic field H_r presented in Fig.9. It is seen that it practically does not change It should be noted that the change in H_r leads to a change in the spectral composition of the oscillation. On Fig. 9 shown changes c_{iz} longitudinal component phase velocity wave on frequency. There is a fairly large scatter of values c_{iz} near anode z= 1.5sm. In the middle part and in the channel exit it is considerably smaller than in near anode and in the band of the frequency f=80-700kHz $c_{pz} \sim 0.8 \cdot 10^6$cm/s for 150V discharge voltage. Measurements of phase velocity shows that it increases linearly with increasing discharge voltage. The range of variation c_{iz} is the same as for the azimuthal wave.

Analysis effect of electron temperature oscillation on processes of ionization.

There are two mechanisms that cause oscillation in the ion current. This is oscillations of the electron temperature and plasma potential. One of them leads to instability of the ionization zone; the other is to a redistribution of ion flow, both on the radius and azimuth in the channel SPT, by causing the modulation of ion density both in SPT volume so in time. In the channel there are two types of oscillations. Synchronous oscillations can lead to instability of the ionization front. Such oscillations are observed in the low-frequency region. They appear as oscillations of the discharge current and total ion flow going out from the SPT[4]. Azimuthal variations can lead to modulation of ion density in azimuth, but not cause a change ion current on the channel cross section. Experiments have shown that the electron temperature oscillations amplitude a can be as high as 30% of its dc component.

Ionization cross section is $\sigma_i = 4.4 \cdot 10^{-14} \cdot \ln(E_0/I)/E_0 \cdot I$ – Lotz formula , E_0- electron energy, I-ionization energy, for Kr I = 14eV. The electron temperature in the channel can vary then the ionization rate is

$$Q(T_e) = \int_{14}^{\infty} n(E_0) dE_0 v_e \sigma_i(E_0) N$$

If assume, that density neutrals N in the channel is changing little, the electron distribution n(E$_0$) is Maxvellian, can calculate relative ionization rate

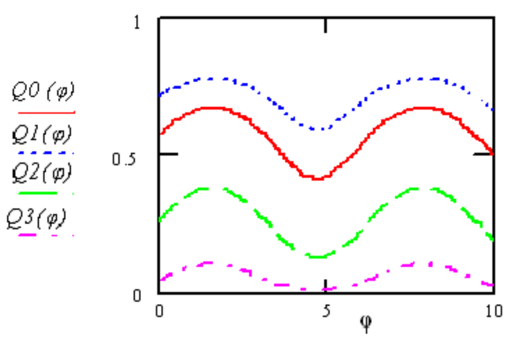

Figure10. Change the ionization rate due to electron temperature oscillation for different values T_{e0}

Q0 (φ) - T_{e0} = 20ev, $Q1$ (φ) - T_{e0} = 30ev, $Q2$ (φ) - T_{e0} = 10 eV, $Q3$ (φ) - T_{e0} = 5ev

$Q(\varphi) = Q(T_e) / Q(T_{e0})$ in channel, assuming that $T_e = T_{e0}(1+ 0.3\sin(\omega_0 t - k_\varphi \varphi))$

As can be seen Fig. 10 rate $Q(\varphi)$ decreases with increasing Te_0. If for Te_0 = 5eV $Q(\varphi)$ reaches 100%, then for Te_0 = 30eV $Q(\varphi)$ is less than 10%.

Estimates show, that together with the fundamental harmonic, which determined by oscillation in T_e, harmonics of multiple of the main are arising.

The azimuthal oscillations of the plasma potential lead also to a redistribution of ion density in azimuth. On Fig. 11 shown the calculated ion current density in azimuth, which were obtained by calculating dynamics of ions in azimuthal field into channel for oscillation period is much larger than time of being ions in channel (f = 100kHz, the phase velocity of the wave v =1.3·10^6 cm/s).

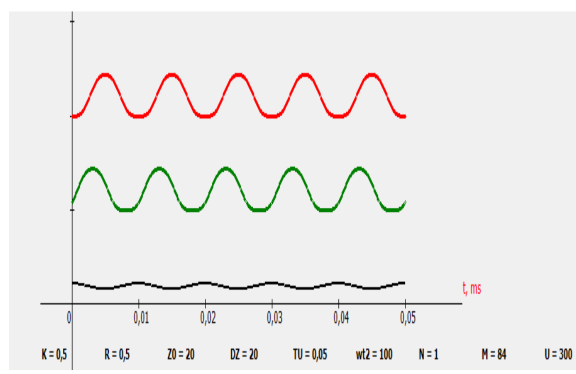

Figure11. Changing the ion current density J_i at the exit at the points that are shifted relative to each other by a quarter periods.

Electrostatic field and the oscillation of the plasma potential are described by the following expression.

$U_p = U_d\, \alpha \cos(\omega t\text{-}nky)\, exp\text{-}(z0\text{-}z)2/b$,

where $U_d\, exp\text{-}(z0\text{-}z)2/b$, - unperturbed value of electric field strength along the channel, α - the oscillation relative amplitude, $k= 1/R$ - wave number, R-average radius of the channel, ω=2π*f, b=2.5.*

Values $v_{i\varphi}$, $v_{i\varphi}/v_{iz}$ depend both on ion birth place and the wave phase, which is installed at the time of his birth.

Upper two curves are amplitude $\hat{J}_i$, calculated at the points shifted in azimuth $\Delta\varphi \approx \pi/4$, the lower curve is amplitude oscillations of the plasma potential. It is seen that the azimuthal wave of plasma potential leads to modulation of ion current density in azimuth, with a phase shift ~ π/4 which corresponds to a shift of $\Delta\varphi$.

The electron transport along channel.

As already noted, only collisions of electrons with neutrals and ions can not explain the electrons transport along all channel. However, near the anode, where the magnetic field is small, this mechanism must work. Electrons flow described by the following expression

$j_e = \sigma (E + (grad(n_pT_e e)/n_p)$, where $\sigma = e^2 n_p/\tau m(1+\omega_H^2\tau^2)$ - conductivity, e - electron charge, m - electron mass, $\tau = 1/N\cdot\langle\sigma_{eo}v_e\rangle$ - time electron collisions, $\omega_H = eH/mc$ - frequency of cyclotron oscillations.

Knowing the parameters of the plasma, magnitudes electric and magnetic fields, which shown in Fig. 2,12,13, can calculate $\beta = J_e / J_H = \omega_H\cdot\tau$ the Hall parameter along the channel. The results are shown in Fig. 14.

The first curve $P = J_e / J_H$ was obtained by measuring $J_e = J_d\text{-}J_i$ and calculating the Hall current – $J_H = ecn_pE/H_r$, second curve was obtained under the assumption, that electron transport is effected due to the elastic scattering of electrons on neutrals $P = \omega_H\cdot\tau$.

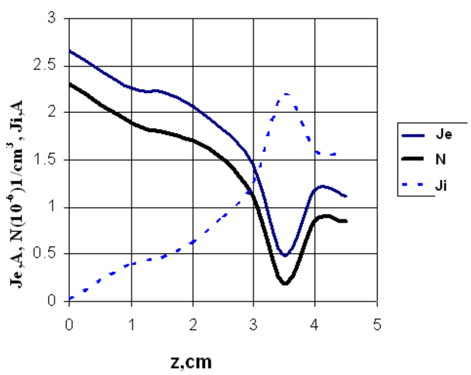

Figure 12. Distribution of the electron current J_e, the density of neutrals N_0, the ion current J_i along the channel.

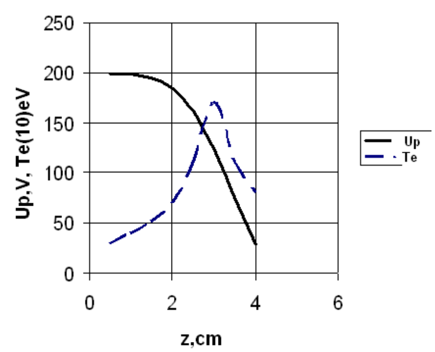

Figure 13.Distribution of the electrical field and electron temperature along the channel

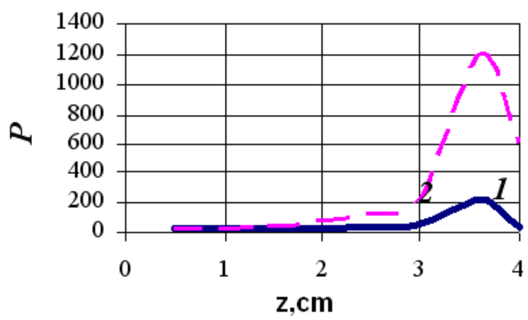

Figure14. The change of the Hall parameter $K = J_e/J_d = \omega_H\cdot\tau$ along the channel,

1 - from the experimental results

2 - elastic scattering of electrons by neutrals.

The fig. 15 shows that collisions with neutrals provides only electron transport in the region adjacent to the anode of *z*< 1.5sm.

In channel, where the magnetic field is significantly more, the frequency of electron collisions with neutrals is too small to support electron diffusion along the channel.

In the channel thruster are observed azimuthal oscillations of electric field and plasma density. Electrons, by drifting in a radial magnetic field H_r, can be move across the magnetic field. Longitudinal electron current J_e can be great, if is established high enough correlation between the oscillations n_p and E_φ.

Studies presented above show that the modulation of the plasma density is directly related with the azimuthal oscillations of the electron temperature (the change of the ionization rate) and the appearance in ions the azimuthal component of velocity. This makes it easy to evaluate the correlation between of oscillations plasma density and electric field. We assume that the oscillations of the ion current density correspond to oscillations of the electron

density in the investigated frequency range. The spectral composition of the azimuthal wave of electric field, gradient of electron pressure $Eo=E+$ grad$((n_pT_e)/n_p)$ and the electron density can be written as a sum of harmonics $E_\varphi=\sum E_o cos(\omega t-k_\varphi\varphi)$ and $n_p=\sum n_{p0} cos(\omega t-k_\varphi\varphi+\alpha)$, where α phase shift between E_φ и n_p.
Then the electron current, which can be transported along the channel,

$$J_{ez}=\frac{ec}{H_rT_0}\int_0^{T_0}\int E_\varphi n_p dtdS$$

Clearly, averaging over the period is different from zero, if $\alpha \neq \pi/2$ and mode harmonic for E_φ and n_p is the same. The phase shift can occur: 1) in time the movement of ions through channel τ_m, if τ_m time is comparable with azimuthal waves period and 2) in the ionization process. Estimate shows, that only time moving of the ions in the channel τ_m since its formation provides shift $\alpha > \pi/4$. Ionization collisions time is much more than time of escape of ions from the ionization region (accumulations of ions not). In Fig. 18 shows the results of calculating electrons diffusion velocity along the channel v_e for z> 1.5. Curve 1 was obtained, as $u_e = (J_d-J_i)/en_p$. Curve 2 was obtained from analysis electrons transfer in the azimuthal field of the wave $u_e=\frac{c}{n_pH_rT\,2\pi\,\text{Re}}\int_0^T\int_0^{2\pi R}E_\varphi\tilde{n}_p dtd\varphi$

The calculations were based on the fact that electron transport is carried out in a wave, amplitude of the harmonics whom has been obtained experimentally. In the middle of the channel is usually used two harmonics, at exit, where there is a high-frequency harmonics, up to 4 harmonics.

As can be seen, these curves are in good agreement, except the region near the exit where the structure of oscillations substantially is different. Despite this, we can conclude that electrons transport in the channel arise due to electrons drift in the azimuthal wave of electric field and the radial component of the magnetic field. Modulation of the plasma density occurs by changes of the ionization rate due to oscillation of the electron temperature, as well as by the influence of the azimuthal wave of electrical field on ions motion.

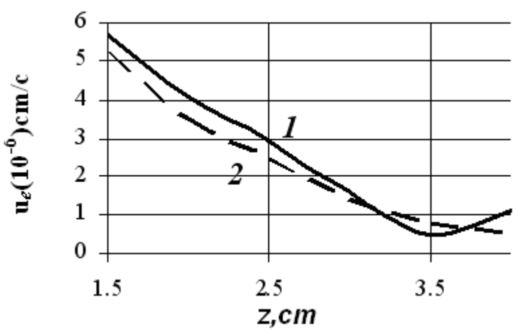

Figure 18. Changing the rate of electrons diffusion along the channel
1 - was obtained as $u_e = (J_d - J_i) / n$, 2 - Analysis of electron transfer in the azimuthal wave field

The electrons heating.

As noted, the nature of electrons heating in the channel SPD is not clear. It was noted that electron temperature oscillations are identical to plasma potential oscillations. We can suggest that the mechanism which causes electrons heating is 1) the interaction of alternating current drift electron with the azimuthal wave component of electric field q_w^0 and 2) the interaction of the longitudinal alternating electron current with the longitudinal wave component of electric field q_w^1.

$$q_w^0=1/T\int_0^T J_{e\varphi}E_\varphi dt \neq 0,\quad q_w^1=1/T\int_0^T \tilde{J}_{ez}E_z dt \neq 0$$

Obviously, the electrons will be gain energy, if their velocity will be in phase with the wave. The oscillation of electron current in the azimuthal direction (drift velocity) will be determined by longitudinal wave component of electrical field is $J_{e\varphi}=en_p\tilde{E}_z/cH_r$. The oscillation of electron current in the longitudenel direction (drift velocity) is

$$J_{ez}=ecn_pE_\phi/H_r.$$

If discuss electron heating q_w^0, in the field of azimuthal wave, it will occur at frequencies above 400 kHz, the phase velocity of these disturbances will be in two times larger than the azimuthal phase velocity of electric field.

It is easy to show that the electrons will gain energy, if the oscillations frequency of the electron velocity and electric field will be the same, and the initial phase shift is different from zero. Then $q_w^0=1/2\pi RT\int_0^T\int_0^{2\pi R}J_{e\varphi}(E_\varphi-d(n_pT_e)/d\varphi)d\varphi dt$.

Confirmation, that this mechanism exist, is the coincidence this values q_w^0 with the energy flux, which is spent on ionization and excitation of the neutral $q_i = 4\ n_p\ I\ /\ N_0 <\sigma_i v_e>$. Estimates show that electrons per cm^3 must to receive energy flux a few watts. In addition it is necessary that the electron energy, which they should receive from these waves, must exceed value *eI*. This is possible if the oscillation frequency is comparable with frequency of electron-neutral collisions $f_c = N<\sigma_{eo} v_e>$. The energy, required for the ionization, must be accumulated by electrons over several periods. Estimates show that f_c is in the range (0.3-1.3) MHz, which coincides with the frequency of longitudinal wave component. Calculations q_w^0 showed that from the wave field the electrons can really get the energy flux sufficient to provide ionization. It should be noted that the ionization collisions frequency in 5-10 times less than value of electrons elastic scattering f_c. I.e. electron heating will be pass in the frequency range till (60-150) kHz. Indirect confirmation that this mechanism observed, is the electron distribution function,[12] which on the tail appear a group of high-energy electrons with energies of 20 - 40 eV.

Conclusions.

Studies of the plasma potential, electron temperature and ion current in the channel of SPT have shown that oscillation at frequencies f <80 kHz are synchronous, the amplitude whom reaches maximum value, oscillations for f> 80 kHz represent a wave, which extends both in the azimuth so and along the channel.

It was found that the oscillations spectrum varies along length of a channel, closer to the exit it becomes more high frequency. Phase velocity v_φ coincides with direction of the drift velocity of electrons. It increases linearly with discharge voltage from ~ $1.3\cdot10^6$ sm/s to ~ $2.7\cdot10^6$ sm/s in range of discharge voltage 170-300V. The phase velocity almost not changes on magnetic field within of variation of Hr more than doubled and not dependent on harmonic frequencies till f<1 MHz.

The longitudinal wave vector coincides with the longitudinal ion velocity. Dependencies the phase velocity of longitudinal waves for the ion current and plasma potential several differ. The phase velocity v_{zp} in 2 times more than v_{zi}. The longitudinal wave component of the plasma potential are observed for f> 400 kHz.

It is shown, that the modulation of ion density in the channel relate to oscillations of plasma potential and electron temperature due to the change of ionization rate and an appearing of azimuthal velocity component. This made it possible to substantiate that electron transport along the channel is carried out due the electron drift in the azimuthal electric field and radial magnetic field. The high correlation between oscillations of electric field and plasma density is determined through the ionization process.

The question of the influence of azimuthal oscillations on the mechanism of electron heating is discussed. It is assumed that the source of electron heating is the interaction of the alternating component of electron drift current with the azimuthal wave component of the electrical field and the alternating component of longitudinal electron current with of the longitudinal wave component of the electrical field. Estimates show that, in conditions which are realized in SPT, is working mechanism of interaction alternating component of electron drift current with the azimuthal wave component of the electrical field.

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