

The influence of potential azimuthal oscillations on outgoing ions dynamics in SPT

IEPC-2009-134

*Presented at the 31st International Electric Propulsion Conference,
University of Michigan • Ann Arbor, Michigan • USA
September 20 – 24, 2009*

A.N. Vesselovzorov, E.D. Dlogach, A.A. Pogorelov, E.B. Svirskiy, V.A. Smirnov
Russian Research Centre 'Kurchatov Institute' Moscow, Russia

Abstract: The investigations of ions velocity components going out a stationary plasma thruster SPT are given in this report.

The experiments have shown the exit ion flow contains fractions of particles with azimuthal and radial components ratio about $V_{\phi}/V_z = \pm 1.7$ and $V_r/V_z = \pm 2$ respectively.

Investigations of plasma potential azimuthal oscillations (spectrum frequencies, phase velocity), which can have influence on ions motion, are represented.

Numerical calculations have shown that ions, moving in a field of an azimuthal wave, gain a velocity V_{ϕ} , which is comparable with experimental data.

An influence of the azimuthal velocity component on the beam divergence and the ion flow to the channel walls of a thruster is discussed.

Nomenclature

| | |
|--------------|--|
| A | = amplitude of plasma potential oscillations with respect to the discharge voltage |
| b | = coefficient of the electric field change into thruster channel |
| E | = electric field intensity |
| e | = electron charge |
| f | = oscillation frequency |
| $J1$ | = ion current on 1st collector sector |
| $J5$ | = ion current on 5th collector sector |
| $J3$ | = ion current on 3rd collector sector |
| $J7$ | = ion current on 7th collector sector |
| J_{in} | = ion current on the internal channel wall |
| J_{out} | = ion current on the outer channel wall |
| I | = ion current |
| k | = wave vector |
| l | = wave length |
| R | = channel circle radius |
| r | = radial coordinate of the point at the thruster exit section |
| t | = time |
| V | = total ion velocity |
| V_r | = radial component of the ion velocity |
| V_{rm} | = maximum radial component of the ion velocity |
| V_{ϕ} | = azimuthal component of the ion velocity |
| $V_{\phi m}$ | = maximum azimuthal component of the ion velocity |
| V_z | = velocity along the thruster axis |
| U | = grid bias |
| U_d | = discharge voltage |
| x | = distance to the observation point from the thruster exit |
| z | = coordinate along the thruster axis |
| z_0 | = coordinate of the electric field intensity maximum |
| δ | = angle defining the analyzer position relatively of the thruster axis |
| φ | = azimuthal coordinate of a point at the thruster exit section |

*The 31st International Electric Propulsion Conference, University of Michigan, USA
September 20 – 24, 2009*

- ω = circular frequency
- Φ = azimuthal wave plasma potential
- Φ_0 = azimuthal wave plasma potential amplitude

I. Introduction

Beam investigations performed earlier were mostly focused on studying the beam divergence and the ion energy without the detailed analysis of the ions velocity distribution. It was believed that a beam divergence is defined only by the radial velocity component which appears during ions motion in the electrical field formed in SPT channel. It is known that this field depends on a configuration of magnetic field and electron pressure gradient¹

Investigations which have been performed near the exit have shown great oscillations of plasma potential and electron temperature, at that these oscillations for $f > 50$ kHz appeared as azimuthal waves.^{2,5}

Calculations have shown that electron temperature oscillations have effect on electrical equipotentials, leading to increase of ion radial velocity component.

Azimuthal waves can become the reason of appearance of ions with the azimuthal velocity component. The tracks direction of particles on channel walls is possible confirmation of such ions.³

Results of this work are especially essential for clear understanding effects of ion velocity distribution on the SPT propulsion performance, and the ions-walls interaction, the latter usually leads to channel material sputtering and therefore reduces thruster lifetime

II. An experimental facility and measurement techniques.

All experiments were conducted in the Kurchatov institute. The thruster model used was SPT-70. Diameters of outer and inner walls were 70 mm and 42 mm respectively and channel depth 37 mm.

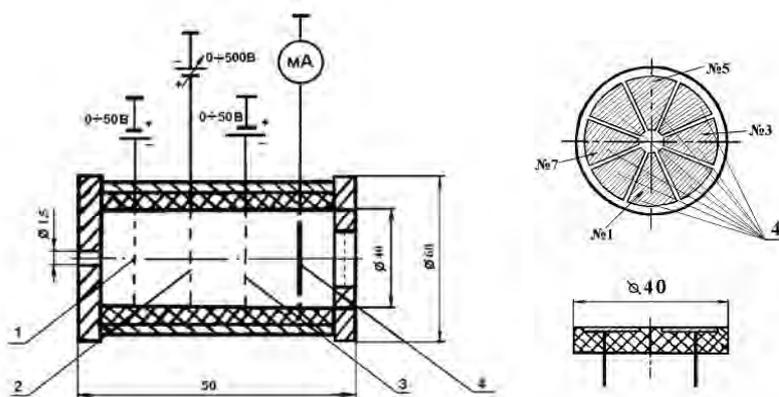


Figure 1, The electrostatic ion energy analyzer
(1, 3 -grids, 2-the analyzing grid, 4- a collector consist of 8 segments)

$$V_{\varphi}/V_z = -\tan(\delta) \sin(\varphi), \quad V_r/V_z = \tan(\delta) \cos(\varphi) - r/z, \quad (1)$$

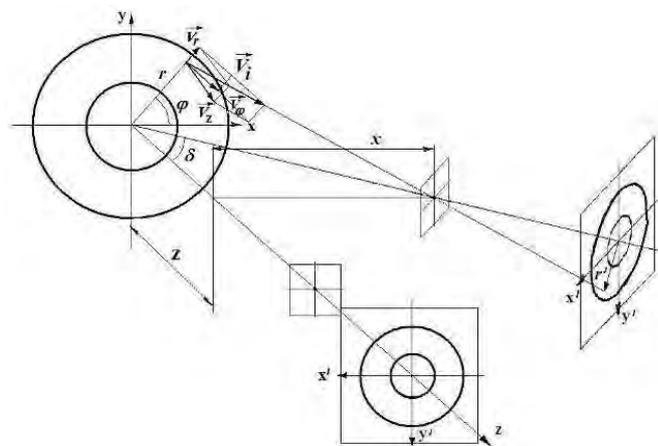


Figure 2. Circuit for the measuring of ions velocity components.

The results had been obtained for operation with Kr, with mass flow rate 1.7 mg/s, discharge voltage $U_d = 200-250$ V. The discharge current had a minimum value $\approx 3.0-3.2$ A for an optimal value of a magnetic field. The steady - state pressure in the vacuum chamber was at $6 \cdot 10^{-5}$ Torr.

For the investigation of ion velocity components the electrostatic ion energy analyzer was used, with a collector consisting of several segments, see Fig.1. If an ion goes out from the thruster exit section and hits upon the device collector segments Fig. 2, then we can calculate velocity components V_{φ}/V_z and V_r/V_z from the following expressions.⁴

where V_z - velocity along the thruster axis, $\tan(\delta) = x/z$, r, φ -coordinates of points at a thruster exit section, the observation point is located at a distance z from a thruster exit and at a radius x from a thruster axis.

Of these expressions it follows, what by means of moving an analyzer comparatively of SPT one can reveal ions with all velocity components. Besides, this device allows analyzing the ion energy distribution for obtaining distinct velocity components.

III. Experimental results.

A. Investigation of ions velocity components in the ion flow leaving the SPT.

During experiments at different positions of an analyzer the ion current coming onto collector segments was measured. Results of these measurements are represented on fig.3.

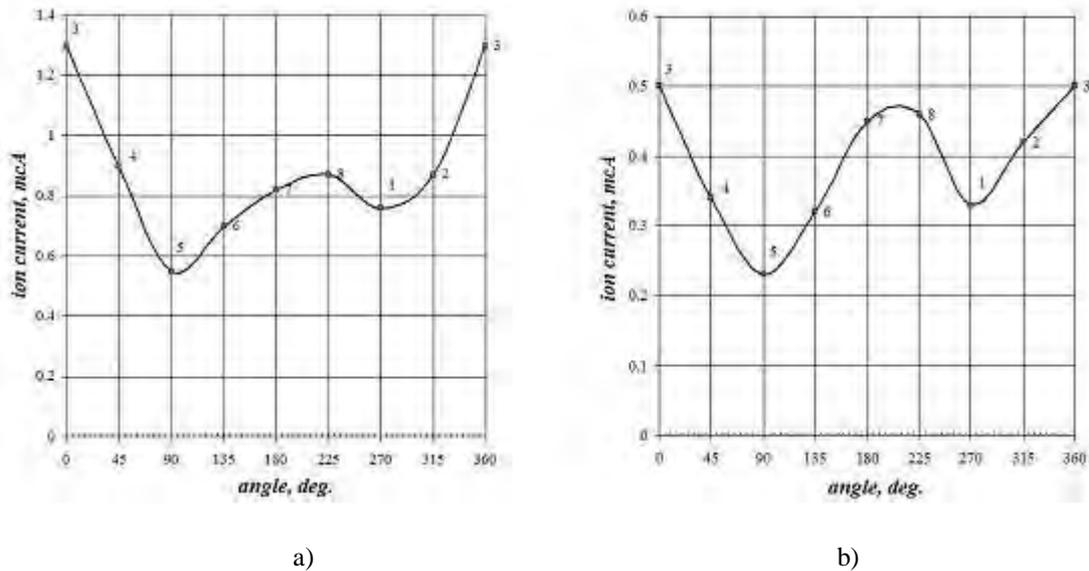


Figure 3. The distribution of ion current on collector segments of multi grid analyzer.
Numbers of segments are denoted by numerals.

The analyzer location with respect to thruster exit a) $z=150\text{mm}$, $x=-90\text{mm}$, b) $z=150\text{mm}$, $x=-60\text{mm}$.

Ions with maximum azimuthal and radial velocity components arrive on segments 1, 5, and 3, 7 respectively, and at that ions moving from a part of a channel adjoining inner and outer walls arrive on different segments (except 1, 5).

From this data follows there are ions with radial and azimuthally components of velocity in the beam.

The ion current value, measured on different segments, differs. The ionic current having the maximum component ratio V_r/V_z is greater than one V_ϕ/V_z .

Figure 3a, b show ions with $V_r/V_z = +0.6 \div -0.69$, $V_\phi/V_z = \pm 0.6$ and $V_r/V_z = +0.4 \div -0.49$, $V_\phi/V_z = \pm 0.4$ respectively.

The dependence of an ionic current with different velocity components on the value of analyzing grid voltage $I(U)$ is shown on figure 4a, c. The ion energy spectrum $-dI(U)/dU$ is represented on Fig.4 b, d.

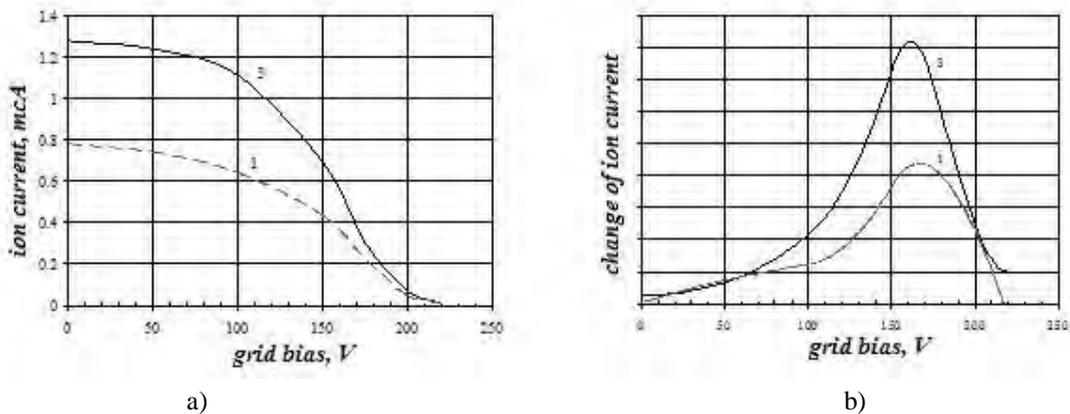
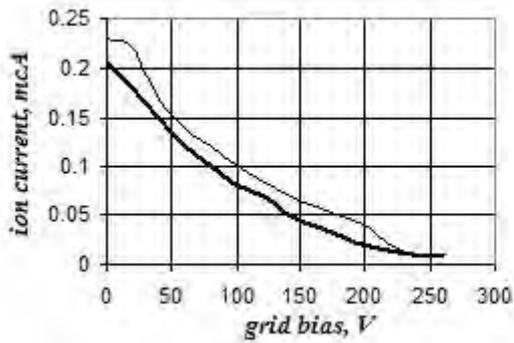
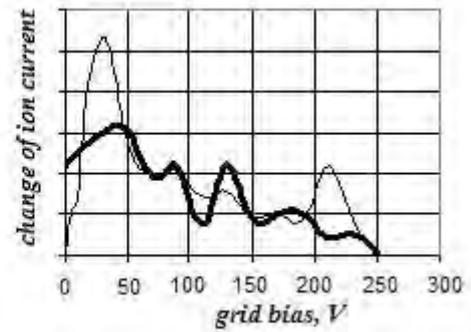


Figure 4a, b $\delta=22^\circ$, curve 1 for ions with maximum values V_ϕ/V_z , curve 3 for ions with maximum values V_r/V_z



c)



d)

Figure 4 c, d $\delta=60^\circ$, the thick curve for ions with maximum values V_ϕ/V_z , the thin curve for ions with maximum values V_r/V_z

It is evident, that energy spectra for different ion groups and the same arrangement of an analyzer is close. If arrangements of an analyzer substantially differ, energy spectra are varied.

In reality ions with $V_r, V_\phi \leq V_z \delta=22^\circ$ have a standard energy spectrum (slow ions are missed, the energy of a distribution maximum amounts to about $2/3 eU_d$). Spectrum of ions, which have $V_z \leq V_r, V_\phi, \delta=60^\circ$, becomes low-energy, and a significant part of ions appears with an energy 20-100 eV. Evidently these ions are emerged near the exit thruster.

B. Structure of an azimuthal wave.

The ion dynamics depends on an electrical field strength E . The azimuthal wave plasma potential is described as $\Phi = \Phi_0 \sin(\omega t - kl)$, where ω - frequency, t - time, k - wave vector, l - wave length, then $E = -d\Phi/dl \sim \Phi_0 k$. Therefore a wave action on an ion must increase with increasing k .

A maximum wave length must be equal to the channel circle $2\pi R$ and $k=1/2\pi R$. A radius of ring channel lies within the limits $R = (3.5 - 2.1)$ cm.

Investigations have shown that plasma potential oscillations near the anode in the optimal operation regime are low-frequency and oscillation relative amplitude amounts to 10% of its constant value. Near the channel exit a relative level of oscillations has increased to 30% and spectrum is enriched with high frequency harmonics.

An azimuthal wave is observed at a frequency $f > 50$ kGz, and a phase velocity V_p for $U_d=200$ V is $2 \cdot 10^6$ cm/s. The spectrum composition of plasma potential oscillations which has been obtained close to the exit is shown in table 1.

Table 1.

| f , kGz | 50 | 60 | 80 | 100 | 110 | 140 | 160 | 190 | 220 | 290 | 320 | 400 |
|------------------|-----|------|------|------|------|------|------|------|------|------|-----|-----|
| Φ_0 | 1,6 | 0,15 | 0,43 | 0,18 | 0,14 | 0,18 | 0,15 | 0,19 | 0,13 | 0,11 | 0,1 | 0,1 |
| $\Phi_0 \cdot k$ | | | 0,43 | | | | 0,3 | | 0,39 | | 0,4 | 0,5 |

If we suppose that the wave length equals to the average channel circle length and if to take into account a wave phase velocity, the minimum azimuthal wave frequency is $f > 80$ kGz. It is possible to see that though an amplitude Φ_0 decreases with a harmonic frequency, the value $\Phi_0 k$ electrical field strength amplitude changes slightly.

C. Numerical investigations of azimuthal oscillations influence on dynamics of ions.

The evaluation of potential azimuthal oscillations influence on an ion trajectory in a SPT channel was performed by using a numerical model.^{6, 7} Special considerations was given to the possibility of ions' gaining azimuthal velocity component in the potential wave field. The potential along the channel radius was set constant for simplicity.

Full ion energy does not exceed eU_d for ions with substantial component velocity. The ionization rate within the ionization area is set constant. Phases of ion generation are distributed uniformly along the wave period.

Ion trajectories were calculated by integration of dynamics equation where a magnetic field influence was ignored. Oscillations of a potential along azimuthal direction were set in the form

$$\Phi(z, \varphi, t) = U_d A \exp(-(z_0 - z)^2/b) \sin(\omega t - k\varphi),$$

where A is the relative amplitude of oscillations.

Along the channel axis the electric field intensity is bell-shaped with peak value at $z=z_0$, and with the width b . The parameters in the model were chosen based on experimental data. The oscillations amplitude maximum is correlated with the electron temperature maximum.

Since a real oscillations spectrum consists of many harmonics with different amplitudes and frequencies, the numerical calculations were carried out for different sets of harmonics.

The numerical analysis has shown the azimuthal velocity component of ions grows with increasing of amplitude and frequency of oscillations. The phase shift between harmonics does not lead to notable change of the average exit angle $\langle V_\phi/V_z \rangle$, but considerably raises (by two times) the maximum angle V_ϕ/V_z . Calculations of wave velocity influence on the azimuthal component have shown that the phase speed decrease leads to the azimuthal component increase.

The results of numerical calculations have shown that ions, moving in field of plasma potential azimuthal wave, should obtain an azimuthal component of velocity of the same order as observed in experiments.

III. Discussions of experimental results.

A. Oscillations of an ion current.

Fluctuations of ion current which are measured on different sectors are identical. The appreciable amplitude up to $0.3J_d$ is observed in the low-frequency band $f < 30$ kHz, these fluctuations correspond to fluctuations of a discharge current and are obviously caused by the ionization instability. A level of fluctuations for high-frequency harmonics $f > 100$ kHz is considerably less and amounts only to $(0.05 - 0.1) J_d$ for ions with small azimuthal velocity and for ions with maximal azimuthal velocity.

The current modulation absence of ions having greater azimuthal velocities, obviously, can be explained by the fact that these ions reach the collector with a full set of phase shifts from the beginning of influence on them of azimuthal waves. It occurs for several reasons; the azimuthal electric field is formed by several harmonics, the ionization zone occupies the most part of the channel, the ions movement time till the registration point is appreciably more, than the azimuthal oscillations period.

B. Streams of ions on channel walls.

It is of interest to analyze the azimuthal ion velocity influence on ions flows directed onto the channel walls. If we consider the movement of ions in polar coordinate system, velocities of ions going to internal and external circular channel walls have opposite directions. The azimuthal velocity component leads to increase of the radial component directed from the center, therefore the collision time decreases for ions moving to the external wall and increases the for ions moving to the internal wall.

Calculations have shown that a presence of an azimuthal velocity leads to an occurrence of the ionic group with higher radial velocity component directed to the external insulator the value V_r / V_z increasing with oscillations amplitude. The ions fraction with radial velocity component raised considerably (by several times) amounts to one percent and less.

Obviously, the ions which leave the channel area adjoining to its internal wall should have values $(V_\phi + V_r)/V_z$ greater than the ions which leaves the channel area adjoining to its external wall. An indirect confirmation of it is the relative change in the value of ion current with the maximal velocities and going out of the channel area adjoining to its internal and to external wall J_{out} / J_{in} depending on $\tan(\delta)$. In particular for $\tan(\delta) = 0.6$ $J_{out}/J_{in} = 1.5$, and for $\tan(\delta) = 0.4$ $J_{out}/J_{in} = 1$.

Hereinafter the sum of different components of velocity is considered as a vector sum.

C. Ionic beam divergence.

It is interesting to analyze the contribution of azimuthal velocity on the beam divergence $(V_\phi + V_r)/V_z$.

It is necessary to note, that the measurement technique of velocity components is executed in such a manner that one half the collector registers ions came from the channel part adjoining to its external wall, while the other half of the collector registers ions from the internal half of the channel.

Obviously, the full ions velocity is $V = V_z + V_r + V_\phi$. The value of thrust will be defined by the longitudinal component $V_z = V - (V_r + V_\phi)$. Reducing the value V_ϕ and assuming that V is a function of a discharge voltage, it is possible to increase the longitudinal component the same as thrust characteristics of SPT. In reality to estimate the influence of the azimuthal velocity on thrust characteristics it is necessary to have the data of ion velocity distribution function which is rather difficult a problem.

Measurements performed allow estimating qualitatively the contribution of V_r , V_ϕ on the beam divergence.

So from the expression (1) follows, that $(V_r + V_\phi)/V_z = (\tan^2(\delta) - 2 \tan(\delta) \cos(\phi) r/z + (r/z)^2)^{1/2}$.

It is obviously, that sectors 3 and 7 register ions with maximal radial $V_{rm}/V_z = (1 \div 0.93) \tan(\delta) - r/z$ and minimal azimuthal $V_\phi/V_z = (0 \div 0.38) \tan(\delta)$ velocities.. Sectors 1 and 5 register ions, with maximal azimuthal $V_{\phi m}/V_z = (1 \div 0.93)$

$\tan(\delta)$ and minimal radial $V_r/V_z = (0 \div 0.38) \tan(\delta) - r/z$ velocities. Thus average values V_ϕ and V_r at corresponding sectors differ more than in 5 times.

It is interesting to analyze the dependence of ionic currents registered by sectors 1, 5 and accordingly by sectors 3, 7 $(J1+J5) / (J3+J7)$ on the arrangement of the analyzer $\tan(\delta) = x/z$.

Apparently, the ion fraction with $V_{\phi m}$ velocity component is less than the ion component with $V_{r m}$ velocity component and it decreases from 0.78 for $\tan(\delta) = 0.07$ down to 0.5 – 0.6 for $\tan(\delta) = 0.6$. It means the contribution of a radial velocity in increasing the beam divergence is more essential. Estimations show what if a thrust loss due to the total beam divergence is about 10 % then radial and azimuthal components contribute about 6 % and 4 % respectively.

At the same time, absolute values $V_{\phi m}$ and $V_{r m}$ and V differ slightly. Hence, the beam emittance will be limited by the maximal value $V_m/V_z \sim V_{\phi m}/V_z, V_{r m}/V_z$. Although the electric fields leading to an occurrence of components V_ϕ and V_r are different, the reduction either of them should not lead to a change in the emittance, but should lead to change of the beam brightness within the limits of this phase area.

IV. The conclusion.

1. The investigations of velocity components distribution of the ions in the beam of a stationary plasma thruster have shown, that there are ions with an azimuthal velocity component V_ϕ/V_z , and a radial velocity component V_r/V_z which vary within the limits of ± 0.9 and of $-1.2 \div +0.74$ respectively.
2. In SPT channel azimuthal plasma oscillations are revealed and they can influence on ion dynamics. The spectral structure of these oscillations includes several harmonics, the waves phase velocity increases linearly with the discharge voltage.
3. Results of numerical calculations have shown that ions moving in the field of a plasma potential azimuthal wave obtain the azimuthal velocity component comparable with the values observed in experiments.
4. The presence of azimuthal component should lead to redistribution of the streams falling onto channel walls. The ion flow on the external channel wall should increase and should decrease on the internal channel wall.
5. The ion azimuthal velocity component increases the beam divergence but in smaller degree, than the radial component.
6. While considering thruster characteristics it is necessary to take account of the influence of azimuthal velocity component on the thrust value and the thrust efficiency.

Acknowledgments

This research was supported by the Russian Fund Basic Research through Grant No 06-08-00873.

References

Books.

¹A.I. Morozov Physical's foundation space ERT, *Atompubl*, Vol 1, 1978, p. 260.

Periodicals

²A.I. Morozov, Yu.V. Esipchuk, A.M. Kapulkin, V.A. Nevrovskiy, V.A. Smirnov *Sov. Phys. Tech. Phys.* XLIII, 5, p.972, 1973.

³B.A. Arkhipov., R.Y. Gnizdor., N.A. Maslennikov., *Plasma physics*, Vol. 23, No. 7, 1997, pp. 635 – 645.

⁴I.P. Zubkov, A.J. Kislov, A.I. Morozov, *Sov. Phys. Tech. Phys.* Vol. XLI, No. 5, 1971, p. 880.

Reports, Theses, and Individual Papers

⁵V.A. Smirnov, Temperature electron oscillations T_e into ACDE, *thesis report, 3-conference on plasma acceleration, Minsk*, 1976, p.12.

⁶A.N. Vesselovzorov, E.D. Dlougach, A.A. Pogorelov, E.B. Svirskiy, V.A. Smirnov, *Report of RFBR*, 2006, No. 06-08-00873.

⁷A.N. Vesselovzorov, E.D. Dlougach, A.A. Pogorelov, E.B. Svirskiy, V.A. Smirnov, *Report of RFBR*, 2007, No. 06-08-00873.