Influence of Anomalous Transport Phenomena on Onset of Neoclassical Tearing Modes in Tokamaks

S. V. Konovalov,[1), 2)] A. B. Mikhailovskii,[1)] T. Ozeki,[2)] T. Takizuka,[2)] M. S. Shirokov,[1)] N. Hayashi [2)]

[1)]Institute of Nuclear Fusion, Russian Research Centre "Kurchatov Institute", Moscow, Russia
[2)]Naka Fusion Research Establishment, Japan Atomic Energy Research Institute, Naka-machi, Naka-gun, Ibaraki-ken, Japan

e-mail contact of main author: konoval@nfi.kiae.ru

Abstract. Influence of anomalous perpendicular heat transport and anomalous ion perpendicular viscosity on conditions of Neoclassical Tearing Mode (NTM) onset is studied theoretically. Series of various parallel transport mechanisms competitive to anomalous cross-island heat transport in formation of the perturbed electron and ion temperature profiles within the island are considered. Analytical solutions to respective heat balance equations were found and perturbed temperature profiles were calculated rigorously. The partial contributions from the plasma electron and ion temperature perturbations in the bootstrap drive of the mode and magnetic curvature effect were then accounted in construction of a generalized transport threshold model of NTMs. Taking into account the curvature effect weakening in the generalized transport threshold model predicts notable improvement of NTM stability. The anomalous perpendicular ion viscosity was shown to modify collisionality dependence of polarization current effect reducing it to the low collisionality limit. The bootstrap drive of NTM in the presence of anomalous perpendicular ion viscosity was found to be dependent on the island rotation frequency and direction. For island rotating in direction of the electron diamagnetic drift viscosity effect was shown to be stabilizing. The role of viscosity effect grows rapidly with rise of the plasma ion temperature.

1. Introduction

Neoclassical tearing modes , NTMs, are known to limit maximum attainable plasma pressure, degrade confinement and at worst culminate in disruption of tokamak discharges. Thus, NTMs should be either avoided or suppressed in reactor relevant plasmas. Both avoidance and/or suppression algorithms depend crucially on knowledge of the NTM onset (threshold) physics. Besides, it is mostly the uncertainties in description of threshold mechanisms that deprive NTM evolution models of quantitative predictive capability, which is necessary for development of a feedback system for their reliable control in a fusion reactor like ITER.

The evolution of the NTM is described in terms of modified Rutherford equation of the form

$$\dot{W} \sim \Delta' + \Delta_{bs} + \Delta_{mw} + \Delta_{p}\,, \qquad (1)$$

where W is the magnetic island width, Δ' is the conventional tearing mode stability parameter, Δ_{bs} is the contribution of the perturbed bootstrap current, which is supposed to be the only drive of NTM, Δ_{mw} and Δ_{p} stand for the curvature (magnetic well) effect and contribution from the polarization current, respectively. This equation is obtained by integrating the Ampere law across the nonlinear internal region and matching the result with Δ' determined from the outer region of the mode. Only perturbation of the parallel current $\widetilde{J}_{\|}$ is accounted in (1), where separate contributions correspond to different components of $\widetilde{J}_{\|} = \widetilde{J}_{bs} + \widetilde{J}_{mw} + \widetilde{J}_{pol}$. In this report we shall use the analytical expression for the perturbed bootstrap current of the form derived in [1] in the large aspect ratio approximation, keeping in mind that for practical applications approaches of Refs. [2] or [3] can be more relevant.

$$\tilde{J}_{bs} = -2.46\frac{\varepsilon^{1/2}c}{B_\theta}\left[(T_{0e}+T_{0i})\frac{\partial\tilde{n}}{\partial x} + 0.40n_0\frac{\partial\tilde{T}_e}{\partial x} - 0.17n_0\frac{\partial\tilde{T}_i}{\partial x}\right]. \tag{2}$$

Particular expressions for magnetic well and polarization currents should be found from the current continuity equation in the vicinity of the island

$$\mathbf{B}\cdot\nabla\frac{\tilde{J}_\parallel}{B} = -\nabla\cdot\frac{\mathbf{B}\times\nabla\tilde{p}}{B^2} - \nabla\cdot\frac{\mathbf{B}}{B^2}\times\left(\rho\frac{d\tilde{\mathbf{V}}}{dt} + \nabla\cdot\boldsymbol{\pi}\right), \tag{3}$$

where the terms with perturbed pressure gradient and time derivative of the perturbed velocity determine magnetic-well and polarization currents, respectively. Spatial integration of the above components of the perturbed parallel current yields respective contributions $\Delta_{bs,mw,pol}$ in Eq. (1). Particular expressions for Δ_{mw} for magnetic island problem are discussed in [4].

As it was originally shown in [5,6] at small island width finite cross-island heat transport prevents the pressure flattening inside the island and reduces the bootstrap drive of the mode. This transport correction was expressed in terms of additional weakening factor in the expression for bootstrap drive in form of the ratio $W^2/(W^2 + W^2_{crit,bs})$, where W_{crit} is a critical island width below of which the perpendicular transport corrections become important. Another form of the weakening factor, $W/(W^2 + W^2_{crit,mw})^{1/2}$, was proposed in [7,8] for the contribution of the magnetic-well current. As it was explained in [9] the difference in the bootstrap drive and curvature effect weakening is due to the two reasons. The first is that perturbed pressure determining the both contributions is oscillating with respect to island cyclic variable. The second is that the magnetic well current corresponds to the oscillating part of the perturbed pressure, while the bootstrap current corresponds to the averaged one. It is this additional averaging that yields additional small factor of the order of W/W_{crit} for the bootstrap drive in the limit of the strong perpendicular transport.

In the initial paper [5] analysis was addressed mainly to calculation of the perturbed electron temperature profile and respectively to electron contribution to the bootstrap drive of the mode. However it is clear that ion contribution should be also taken into account. In the approximations used here [see Eq. (2)] it is even stabilizing for NTM. Also it is evident that the perturbed ion and electron temperatures are determined by essentially different transport mechanisms. Therefore, the aforementioned forms for the weakening factors for bootstrap drive and magnetic well effect should be generalized with taking account of the, first, partial contributions of plasma species and, second, the varieties of transport mechanisms involved into the formation of the perturbed temperature profiles

$$\Delta_{bs} = \sum_{A=n,T_e,T_i} a_{bs,A}\frac{W}{W^2 + W^2_{bs,A}}, \qquad \Delta_{mw} = \sum_{A=n,T_e,T_i} a_{mw,A}\frac{1}{W + W_{mw,A}}. \tag{4}$$

where characteristic island widths $W_{bs,A}$ and $W_{mw,A}$ are determined by the combination of transport mechanisms governing the establishment of the perturbed profiles[10,9]

$$\frac{1}{W^2_{bs,A}} = \sum_k \frac{1}{W^2_{bs,A,k}}, \qquad \frac{1}{W_{mw,A}} = \sum_k \frac{1}{W_{mw,A,k}}. \tag{5}$$

Here summation is taken over k different transport mechanisms.

At the present we do not consider particle transport and restrict ourselves to analysis of the electron and ion heat transport only. Then in the following we will omit density gradient from expressions for bootstrap and magnetic well currents. Then, calculation of the bootstrap drive with use of Eqs. (2) and (4) yileds

$$\Delta_{bs} = 3.89\frac{\varepsilon^{1/2} r_s W}{s}\left[\frac{0.40\beta_{pe}}{L_{Te}\left(W^2 + W_{bs,e}^2\right)} - \frac{0.17\beta_{pi}}{L_{Ti}\left(W^2 + W_{bs,i}^2\right)}\right]. \quad (6)$$

For magnetic well effect we adopt the simplified expression[2]

$$\Delta_{mw} = -3.16\frac{\varepsilon^2 r_s}{s^2}\left(1 - \frac{1}{q^2}\right)\left[\frac{\beta_{pe}}{L_{Te}\left(W + W_{mw,e}\right)} + \frac{\beta_{pi}}{L_{Ti}\left(W + W_{mw,i}\right)}\right] \quad (7)$$

Here $\beta_{pe,i}$ are partial electron and ion poloidal beta, and $L_T = -T/T'$. Magnetic well effect in the form of Eq. (7), coincides with commonly used simplified expression in terms of parameter D_R (see Ref.11). The applicability of this approximation is discussed in details in Ref. [4], where, in particular, it was shown that magnetic well effect for magnetic islands should differ from D_R effect relevant to resistive interchange mode due to the narrowness of the resistive layer in comparison with magnetic island width as well as from the magnetic well for ideal kink modes because of the difference in the geometry of the problems.

Several important steps for calculation of the bootstrap drive weakening were taken in recently published papers [10,12,13]. The most of the heat transport equations in [10,12,13] were solved with use of the model approach. In the Section 2 we report results of more rigorous analysis (see for details [14]) which allows us, firstly, to clarify results of [10,12,13] relevant to the bootstrap weakening and, secondly, to calculate accurately the transport corrections to the magnetic well effect. In particular we show that in the small island limit the relative role of the magnetic well effect essentially rises and at the island width of the order of typical value of $W_{crit,bs}$ it leads to full suppression of the NTMs.

Transport corrections to the bootstrap drive and magnetic well effect are essential at sufficiently high, typically anomalous, perpendicular heat conductivity. However, it is known that perpendicular heat conductivity and perpendicular viscosity are of the same order of magnitude. In Section 3 we correct previously reported results of [15,16] on the viscous contribution to the bootstrap drive of the mode and show that it is stabilizing for islands rotating in the electron (not ion[15,16]) diamagnetic drift direction. This finding makes difficult direct application of the transport threshold model of the NTMs taken alone to the interpretation of the experimental data from tokamaks where neoclassical islands were found to rotate in the ion diamagnetic drift direction. To find a stabilizing mechanism compensating the viscous contribution to the bootstrap drive we turn to the analysis of the polarisation current effect. Then we show in the Section 4 that anomalous perpendicular viscosity brings the collisionality dependence of the polarisation current to the limit of weak collision. This result further decreases an applicability of the conventional polarisation current effect to be a reason providing the beta threshold for NTM onset. Then we discuss possible alternative mechanisms of stabilization. Summary and conclusions are given in Section 5.

2. Generalized transport threshold model of NTM

There is a series of different parallel transport mechanisms competitive to anomalous cross-island heat transport in formation of the perturbed electron and ion temperature profiles within the island. Here we consider the 1) original model of [5] in which perpendicular heat conductivity is balanced by the parallel one

$$\nabla \cdot \mathbf{q} = 0, \qquad \mathbf{q} = -n_0 \left(\chi_{\|} \mathbf{b} \nabla_{\|} + \chi_{\perp} \nabla_{\perp} \right) T. \tag{8}$$

Characteristic scale that appears in this problem from balance of parallel and perpendicular heat transports is

$$W_{col} = 2^{3/2} \left(\frac{L_s^2 \chi_{\perp}}{k_y^2 \chi_{\|}} \right)^{1/4}, \tag{9}$$

where $k_y = m/r_s$, $L_s = q_s R/s$ is the shear length, $s = rq'/q$ is the shear. Then, according to [10,12,13], we consider generalized versions of Eq.(8), taking into account 2) island rotation[10]

$$n_0 \frac{d_0 T}{dt} = -\frac{2}{3} \nabla \cdot \mathbf{q}_{\perp}, \tag{10}$$

which determines the characteristic island width

$$W_{rot} = \left(\frac{128\sqrt{2}}{3\pi} \frac{\chi_{\perp}}{\omega} \right)^{1/2} \tag{11}$$

and 3) parallel plasma inertia[12,14]

$$\rho_0 c_{is}^2 \nabla_{\|} V_{\|} = -\frac{2}{3} \nabla \cdot \mathbf{q}_{\perp}, \qquad \rho_0\, d_0 V_{\|}/dt = -n_0 \nabla_{\|} T \tag{12}$$

where $\mathbf{q}_{\perp}$ is given by the second of Eqs. (8) with $\chi_{\|} = 0$, $\rho_0 = M_i n_0$ is the plasma mass density, $c_{is} = \left(T_0 / M_i \right)^{1/2}$, $d_0/dt = \partial/\partial t + \mathbf{V}_E \cdot \nabla$, and $\mathbf{V}_E$ is the cross-field drift velocity, ω is the island rotation frequency. The inertial model (12) sets the characteristic island width

$$W_{inert} = \left(\frac{128\sqrt{2}\pi}{3} \frac{\omega L_s^2 \chi_{\perp}}{k_y^2 c_{is}^2} \right)^{1/4}. \tag{13}$$

Another mechanism of parallel transport competitive to the cross island heat conductivity is the heat convection. For this case we shall adopt the MHD description given in Ref. [13]

$$\nabla_{\|} q_{\|} - \frac{3}{2} \chi_{\perp} \frac{\partial^2 p}{\partial x^2} = 0, \qquad \frac{5}{M} \nabla_{\|} (pT) - \chi_{\perp} \frac{\partial^2 q_{\|}}{\partial x^2} = 0. \tag{14}$$

Here $q_{\|}$ is the parallel heat flux for the given plasma specie, M is the particle mass. Characteristic scale length in the model (14) is

$$W_{conv} = \left(\frac{2^{11/2} \chi_{\perp} L_s}{c_s k_y} \right)^{1/3}, \tag{15}$$

where $c_s = \left(5T_0 / 3M \right)^{1/2}$ is the “generalized” speed of sound.

Remarkable feature of transport equations (8,10,12,14) is that all of them can be solved rigorously. For this we distinguish far and close regions of perturbation, find analytical solutions in these regions and after matching them arrive at the analytical expressions for perturbed temperature profiles. Then these profiles are used for calculation of the bootstrap drive and curvature effect in the limit of strong perpendicular transport and combined with the standard case corresponding to the temperature profiles flattened inside the island. All details for this procedure can be found in Ref. [14]. Here we just present results of these calculations to be used in expressions (5) for bootstrap drive:

$$W_{bs,a} = \left\{ W_{bs,col}, W_{bs,conv}, W_{bs,inert}, W_{bs,rot} \right\} = \left\{ 1.80 W_{col}, 1.27 W_{conv}, 1.47 W_{inert}, 1.65 W_{rot} \right\} \tag{16}$$

and magnetic well effect [9]

$$W_{mw,a} = \left\{ 0.80 W_{col}, 0.52 W_{conv}, 0.60 W_{inert}, 0.83 W_{rot} / \left[1 + \ln^2 \left(W_{rot} / W \right) \right] \right\}. \tag{17}$$

It is important to note that coefficient "1.80" in Eq.(16) before W_{col} is exactly equal to that found in [5] numerically. This proves the accuracy of our analytical approach. Also the last coefficient "1.65" in this formula corrects the error in Eq. (5.4) of Ref. [10]. To compare our results for the transport weakening of the magnetic well with that of [7,8] obtained for collisional transport only, we represent "effective" tearing stability parameter corresponding to the limit of strong collisional transport in the form $\Delta'_{eff} = \Delta' + (2\pi)^{3/2} D_R / W_{col}$. One can see that we have twice as large transport correction to Δ' compared with that of [7,8].

Up to now we did not discussed to which plasma species correspond transport equations (8-15). It is evident that parallel convective transport is relevant to plasma electrons. The characteristic value of $W_{bs,col} \sim (\chi_\perp / \chi_\|)^{1/4}$ was widely used in interpretation of experimental data and in predicting the performance of future machines. However in practical applications this expression was often employed for single fluid plasma description with ungrounded use of heat conductivity coefficients attributed to different (electron and ion) channels, i.e., $\chi_\perp = \max\{\chi_\perp^e, \chi_\perp^i\} = \chi_\perp^i$, and $\chi_\| = \max\{\chi_\|^e, \chi_\|^i\} = \chi_\|^e$. For the hot plasma electron convection is apparently the dominant transport mechanism that determines establishment of the perturbed electron temperature profile.

In its turn in formation of the ion perturbed temperature profile perpendicular ion heat conductivity is balanced by the parallel transports associated with ion inertia for an island rotating with subsonic frequency or with island rotation with respect to plasma for the case of supersonic islands. We consider ion transport for sufficiently large island width $W > W_{\min}$, where the lower boundary was taken to be of order of the ion banana width. Then for island, rotating with frequency of the order of diamagnetic ion drift frequency, $\omega \approx \omega_*$, the subsonic (inertial) transport mechanism is dominant, if island width is large enough, $W / W_{\min} > \varepsilon^{-1/2}$. Supersonic (rotational) transport mechanism becomes important only for smaller islands, $1 < W / W_{\min} < \varepsilon^{-1/2}$. Collisional model is hardly appropriate for the calculation of the perturbed ion temperature profile, because of for this we need $\chi_{\|i} > c_s^2 / \omega$ to provide prevailing of the collisional transport over inertial one. While, according to [10], we have an estimate $\chi_{\|i} \approx c_s^2 / (\nu_{ieff} + |\omega|)$, which contradicts to the above inequality.

Our calculations demonstrate that taking into account the curvature effect weakening in the generalized transport threshold model predicts notable improvement of NTM stability. Indeed, let's consider the condition of the full suppression of the NTM by magnetic well effect, i.e. $(-\Delta_{mw}) > \Delta_{bs}$. For illustration we take the expression (6) and (7) at equal electron and ion temperatures and assuming that the perturbed profiles are formed due to collisional mechanism. Then one can see that the magnetic well effect completely stabilizes the mode at the island width $W < W^{comp} \approx 29\varepsilon^{3/2} W_{col}$. The large multiplier "29" here originates from the following reasons: 1) stabilizing ion contribution in the bootstrap drive suggested in Eq. (6) and its stabilizing effect in magnetic well gives here the factor of 2; 2) bootstrap drive falls down faster than magnetic well, $W_{bs,col}^2 / W_{mw,col} \approx 4W_{col}$; 3) bootstrap drive is "naturally" weakened in neglecting the contribution from density gradient by about of factor 4. All together these factors provide that even at sufficiently small $\varepsilon > 0.1$, neoclassical islands of width $W \approx W_{col}$ are suppressed by the "compound" effect of the bootstrap and magnetic well weakening in the presence of the anomalous perpendicular transport.

Taking above said into account we can conclude that generalized transport threshold model of NTM should 1) include the weakening of the magnetic well effect along with that of the bootstrap drive; 2) separately consider the electron and ion dynamics, where dominant mechanisms determining perturbed temperature profiles in majority of practical applications are the convective transport for the electrons and subsonic (inertial) mechanism for ions. In particular, it means that conventional (corresponding to original transport threshold model [5]) scaling law, $\beta_{onset} \sim W_{crit}$, where critical island width was relevant to the bootstrap weakening only, $W_{crit} = W_{crit,bs}$, should be substituted by more complicated one, where along with local plasma parameters should appear the island rotation frequency, through the ion contributions to the bootstrap drive and magnetic well effect.

3. Perpendicular viscosity effect on the bootstrap drive of NTM

Influence of the anomalous perpendicular ion viscosity on the bootstrap drive of the NTM was initially considered in [15,16] and recently revised in [14]. It is shown in [14] that perpendicular viscosity 1) does not affect electron channel of the bootstrap drive; 2) reduces the ion contribution by additional factor of $W^2 / \left(W^2 + W_\mu^2\right)$, where $W_\mu = \left(\mu_{\perp i} / \varepsilon^{1/2} \nu_i\right)^{1/2}$, $\mu_{\perp i}$ and ν_i are the ion perpendicular viscosity and collision frequency, respectively; and 3)gives rise to additional component of bootstrap drive provided by the perturbed electrical field of the island

$$\Delta_{bs,E} = -3.79 \frac{\varepsilon^{1/2} r_s}{sW} \frac{\beta_{pe}}{L_{p_e}} \frac{W_\mu^2}{\left(W^2 + W_\mu^2\right)} \frac{\omega}{\omega_{p_e}}, \tag{18}$$

which is dependent on the island rotation frequency and direction. The important result of [14] is that this viscous contribution to bootstrap drive is stabilizing for the islands rotating to the electron (not ion) diamagnetic drift direction. (In both preceding papers[15,16] a sign was missed in calculation of the perturbed electrical field).

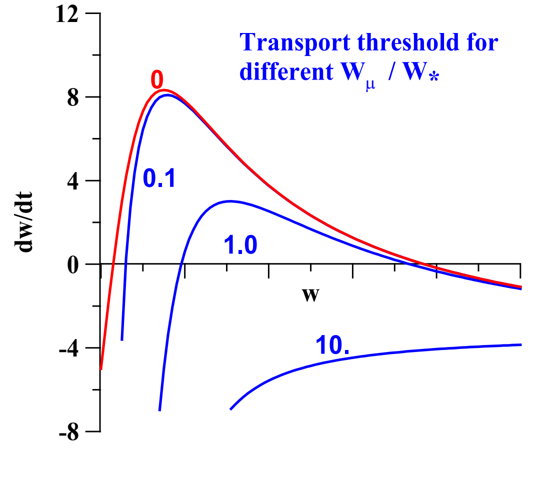
Suggesting that perpendicular viscosity and heat conductivity in tokamaks are of the same order of magnitude, and taken $\mu_\perp \approx \chi_\perp \approx \chi_{\perp g-Bohm} \approx \rho_i^2 V_{Ti} / qR$ we have that $W_\mu \approx \rho_i^2 / \varepsilon^2 \nu_i^{*1/2}$, where $\nu_i^* \equiv \nu_i qR / \varepsilon^{3/2} V_{Ti} < 1$ (in banana regime). Then comparing characteristic island width determined by viscosity with typical initial (detectable) island width, which is of the order of ion banana width, ρ_b, we find that $W_\mu / \rho_b \approx \left(q \varepsilon^{3/2} \nu_i^{*1/2}\right)^{-1} >> 1$. Therefore viscosity effect is *a priori* important in description of the magnetic island evolution near the onset stage. Also the role of viscosity effect grows rapidly with rise of the plasma ion temperature. Considering the dominant contribution to bootstrap drive is to be the electron one and taking convective mechanism of its transport weakening we get $W_\mu / W_{bs,conv} \sim T^{5/3}$. So that if islands rotate in the electron drift direction we have a favorable tendency for NTM stability with rise of the temperature for future fusion devices (see Fig.1). However, in the series of experiments the islands were found to be rotating in the direction of the ion diamagnetic drift. For this case viscous contribution to bootstrap drive (18) is destabilizing and, being insensitive to heat transport corrections, diverges as $1/W$ in zero island limit destroying threshold for NTM onset. Therefore for this case an alternative stabilization mechanism should be found.

4. On the polarization current threshold model

Naturally, the first candidate to cancel out divergent viscous contribution to bootstrap drive is the polarization current effect. However, as it is known (see detailed review [17] and references therein) besides the complicated dependence on the island rotation frequency, the amplitude of this effect being originally small as squared ion Larmor radius is much (about of the two order of magnitude) further decreased with regularization of the perturbed velocity profile[18] (spreading the perturbed velocity jump across the separatrix over the layer of width of the order of ion Larmor radius), and setting the collisionality dependence to its minimum value for the whole range of plasma parameters relevant to experimental observations of the NTM[19]. As it was recently shown (see Sect. 20 of [17]) the perpendicular viscosity effect further emphasizes the later statement. Then the dependence derived in [19] is generalized by

$$g=\frac{\nu_i^2+\varepsilon^{1/2}\omega^2}{\nu_i^2+\omega^2/\varepsilon} \quad\rightarrow\quad \frac{\nu_i^2\left[1+\varepsilon^{3/2}\left(1+W_\mu^2/W^2\right)W_\mu^2/W^2\right]+\varepsilon^{1/2}\omega^2}{\nu_i^2\left(1+W_\mu^2/W^2\right)^2+\omega^2/\varepsilon}. \tag{19}$$

Thus, at sufficiently high viscosity function g tends to the minimal value corresponding to the limit of the weak collisions, $g\rightarrow\varepsilon^{3/2}$ (see Fig. 2). Therefore, the conventional polarization drift effect seems to be too weak to be seen at experimentally detectable island width and to be a reasonable alternative to destabilizing viscous bootstrap current.



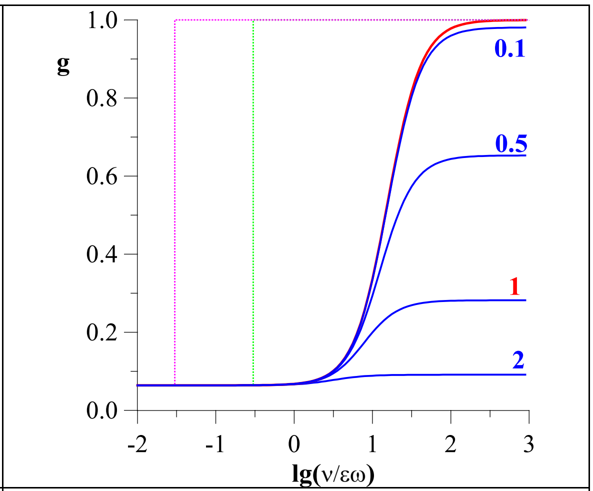


Fig.1 Viscosity effect for island rotating in the electron diamagnetic drift directions at various values of the ratio $0<W_\mu/W_{bs,conv}<10$.	**Fig.2** Collisionality dependence [19] (red), generalized by the viscosity effect at different values of the ratio $0.1<W_\mu/W<2$.

An alternative to neoclassical polarization current effect was suggested in the recently published paper [20]. New terms to island evolution equation was proposed there from accounting neoclassical effects in current continuity equation (3). In particular, neoclassical contribution from the transverse diamagnetic current (first term in r.h.s. of Eq. (3)) which allows for the toroidally oscillating part of perturbed pressure, gives rise to the new contributions to Rutherford equation. One of them, associated with the polarization drift of ions, has a structure and amplitude of order of the standard polarization current effect, but has different scaling (linear) with the frequency. Thus results of [18] on reduction of the polarization drift term for regularized islands can not be directly applied to this case.

5. Summary and conclusions

We have shown that two-fluid approach accounting for partial contribution of the electron and ion dynamics should be adopted in description of the NTM evolution. This is due to that, firstly, their contributions enter in a different way into particular terms in the NTM evolution equation and, secondly, the perturbed electron and ion temperature profiles are determined by the different transport mechanisms. In the case of electrons, the dominant mechanism competitive to the cross-island heat transport is the parallel heat convection, for the case of ions – is the parallel plasma inertia. In the transport threshold model the magnetic well (curvature) effect is as much important as the bootstrap drive weakened by the finite transverse heat conductivity. Generalized transport threshold model accounting for transport weakening of both bootstrap drive and magnetic well effect gives more favorable predictions for NTM stability and should modify scaling law for β_{onset}. Ion transport and perpendicular viscosity bring frequency dependence to the transport threshold model of NTM. Viscous contribution to the bootstrap drive of NTM was found to be of the same order as conventional bootstrap drive for the islands of width typical of the transport threshold model. This contribution is destabilizing for the island rotating in the ion diamagnetic drift direction. In this case an alternative threshold mechanism should be considered.

Acknowledgements
The authors would like to express their appreciation to JAERI and Kurchatov Institute for providing this opportunity of Russia-Japan cooperation. This work was supported by JAERI fellowship program (S.V. Konovalov) and JAERI invitation program of foreign researchers (A.B. Mikhailovskii).

References:
[1] B. N. KUVSHINOV, A. B. MIKHAILOVSKII, Plasma Phys. Rep. **24**, 245 (1998)
[2] M. KIKUCHI, M. AZUMI, S. TSUJI, K. TANI, H. KUBO, Nucl. Fusion **30**, 343 (1990)
[3] O. SAUTER, C. ANGIONI, Y. R. LIN-LIU, Phys. Plasmas **6**, 2834 (1999)
[4] A. B. MIKHAILOVSKII et al., Plasma Phys. Rep. **30**, 595, (2004)
[5] R. FITZPATRICK, Phys. Plasmas **2**, 825 (1995).
[6] N. N. GORELNKOV et al., Phys. Plasmas **3**, 3379 (1996).
[7] H. LUTJENS, J. F. LUCIANI, X. GARBET, Phys. Plasmas **8**, 4267 (2001).
[8] H. LUTJENS, J. F. LUCIANI, Phys. Plasmas **9**, 4837 (2002).
[9] S. V. KONOVALOV, A. B. MIKHAILOVSKII, M. S. SHIROKOV, T. OZEKI, V. S. TSYPIN, "*Suppression of NTM in a tokamak due to prevailing of the magnetic well effect over bootstrap drive in the presence of anomalous transport*", to be published in Plasma Phys. Rep. (2004)
[10] S. V. KONOVALOV, A. B. MIKHAILOVSKII, M. S. SHIROKOV, V. S. TSYPIN, Plasma Phys. Contr. Fusion, **44** , 579 (2002).
[11] A. H. GLASSER, J. M. GREENE, J. L. JOHNSON, Phys. Fluids **19**, 567 (1976).
[12] A. B. MIKHAILOVSKII et al., Phys. Plasmas **10**, 3975 (2003).
[13] A. B. MIKHAILOVSKII, M. S. SHIROKOV, V.S. TSYPIN, S. V. KONOVALOV, T. OZEKI, T. TAKIZUKA, R. M. O. GALVAO, and I. C. NASCIMENTO, Phys. Plasmas **10**, 3790 (2003).
[14] A. B. MIKHAILOVSKII, S. V. KONOVALOV, M. S. SHIROKOV, V. S. TSYPIN, "*Analytical approach for development of the transport threshold model of the neoclassical tearing modes in tokamaks*", to be published in Plasma Phys. Rep. (2004).
[15] S. V. KONOVALOV, A. B. MIKHAILOVSKII, M. S. SHIROKOV, V. S. TSYPIN, Plasma Phys. Contr. Fusion. **44**, L51 (2002).
[16] S.V. KONOVALOV, A. B. MIKHAILOVSKII, M. S. SHIROKOV, V. S. TSYPIN, Physics of Plasmas **9,** 4596 (2002).
[17] A. B. MIKHAILOVSKII, Contrib. Plasma Phys. **43**, No 3-4, 125 (2003).
[18] S. V. KONOVALOV, A. B. MIKHAILOVSKII, Plasma Phys. Contr. Fusion **43,** 1149 (2001).
[19] A. B. MIKHAILOVSKII, V. D. PUSTOVITOV, A. I. SMOLYAKOV, Plasma Phys. Contr. Fusion **42**, 309 (2000).
[20] A. I. SMOLYAKOV, E. LAZZARO, Phys. Plasmas **11**, 4353 (2004).