Integral torque balance in the problem of the plasma toroidal rotation

V.D. Pustovitov

Institute of Tokamak Physics, Russian Research Centre “Kurchatov Institute”, Moscow, Russia

E-mail contact of main author: pustovit@nfi.kiae.ru

Abstract. The study is aimed to clarifying the balance between the sinks and sources in the problem of the intrinsic plasma rotation in tokamaks recently reviewed in [deGrassie J.S., Plasma Phys. Control. Fusion **51** (2009) 124047]. The integral torque on the toroidal plasma is calculated analytically using the most general MHD plasma model with account of plasma anisotropy and viscosity. The contributions due to several mechanisms are separated and compared. It is shown that some of them, though, possibly, important in establishing the rotation velocity profile in the plasma, may give small input into the integral torque. This gives a key to the judicious choice of the directions of necessary studies. The role of the boundary conditions in the problem is discussed. This is a step to relate the plasma rotation to the physical characteristics measured outside the plasma. The analysis shows that an important contribution can come from the magnetic field breaking the axial symmetry of the configuration. In stellarators, this is a helical field which is needed for producing the rotational transform. In tokamaks, this can be the error field, the toroidal field ripple or the magnetic perturbation created by the correction coils in the dedicated experiments. The estimates for the error-field induced torque show that the amplitude of this torque can be comparable to the typical values of torques introduced into the plasma by the neutral beam injection. Therefore, this torque must be considered as an important part of the integral torque balance. The obtained relations allow to quantify the effect that can be produced by the existing correction coils in tokamaks on the plasma rotation, which can be used in experiments to study the origin and physics of the intrinsic rotation in tokamaks. Several problems are proposed for theoretical studies and experimental tests.

1. Introduction

Experiments show that plasma rotation in tokamaks is useful in suppressing the Resistive Wall Mode (RWM) and error-field-induced instabilities [1, 2], but the desired level of rotation is difficult (if not possible) to maintain. On the other hand it is observed in many experiments that the tokamak plasma can rotate ‘spontaneously’ even in the absence of any auxiliary momentum source [3]. This is called intrinsic rotation. The plasma rotation in tokamaks, existing with no known torque injection, still remains a mystery though several models and approaches are proposed to identify the origin of the toroidal momentum and its transport [3, 4]. Our study is aimed to clarifying the integral balance between the sinks and sources in the problem of the plasma toroidal rotation in tokamaks. Attention is paid to formulations with proper treatment of possible toroidal asymmetry, though a deviation from axisymmetry in tokamaks is small. This is known to affect the plasma rotation, but there is no yet reliable predictive theory of the error-field induced braking. Here an approach is proposed allowing evaluation of the integral effects from different physical mechanisms, including the plasma response to the error field, and separation of the dominating contributions. Finally, estimates and proposals to further studies in theory and experiment are given.

2. Momentum equations

The analysis is performed within the single-fluid MHD model incorporating the plasma viscosity, anisotropy and momentum exchange with the neutral beams. This covers a wide area of experimental conditions and different models of the momentum transport. In particular, the Neoclassical Toroidal Viscosity (NTV) effects, which became a popular subject recently [3, 4], can be naturally included.

In a general case the momentum evolution is described by the equation

$$\frac{\partial}{\partial t}\rho\mathbf{v} + \mathrm{div}\overleftrightarrow{\Gamma} = \mathbf{f} \ , \tag{1}$$

where ρ is the mass density of the plasma, $\mathbf{v}$ is its velocity, $\overleftrightarrow{\Gamma}$ is the tensor of the momentum flux, and $\mathbf{f}$ is the force not included into $\mathrm{div}\overleftrightarrow{\Gamma}$. Here we apply (1) to the toroidal plasmas such as that in tokamaks and stellarators. In this geometry we use cylindrical coordinates (R, ζ, z) related to the main vertical axis, ζ is the toroidal angle and $\mathbf{e}_\zeta$ will denote the unit vector along $\nabla\zeta$. Momentum equation in the form (1) contains, as particular cases, all the basic equations used for analysis of the plasma rotation in tokamaks, see [4–8] and references therein.

We consider the integral toroidal force balance obtained from (1) by integrating it, multiplied by $R\mathbf{e}_\zeta$, over the plasma volume. The result is

$$\frac{\partial L}{\partial t} = T \ , \tag{2}$$

where

$$L \equiv \int R\rho v_\zeta dV \tag{3}$$

is the total (or global) toroidal angular momentum of the plasma,

$$T = T_\Gamma + T_f \tag{4}$$

is the total torque on the plasma with

$$T_\Gamma \equiv -\int R\mathbf{e}_\zeta \cdot \mathrm{div}\overleftrightarrow{\Gamma} dV \tag{5}$$

and

$$T_f \equiv \int R\mathbf{e}_\zeta \cdot \mathbf{f} dV \ . \tag{6}$$

Equation for L similar to (2) was used in [7–11] for studying the momentum confinement and intrinsic rotation in the DIII-D and NSTX tokamaks. The main and well determined part of the total torque was the torque from the neutral beams, T_{NBI}. It was found that the experimental observations [3, 7, 9–11] could not be explained by assuming T_{NBI} as the only source of the torque, though this was the only *known* source in those cases. Adding the torque modeling the effect of non-resonant magnetic fields did not help to describe the rotation evolution [7]. The results [7, 9–11] were interpreted as indicating a presence of some additional (or anomalous [7, 9, 11]) torque T_a which was estimated as $T_a \approx -T_{NBI}$ [7, 9].

This is not a minor correction, but an unknown effect of the leading order. Therefore, a step to solution of the intrinsic rotation mystery could be done by analysing the integral (global) torque balance (2). For example, in a steady state with $\partial L/\partial t = 0$ without variations of plasma density and velocity. To move in this direction, we have to calculate T_Γ in (5) and T_f in (6).

3. Physics model

A good starting point for the plasma in the magnetic field (and not only for the cases considered here) can be

$$\overleftrightarrow{\Gamma} = \rho\mathbf{v}\mathbf{v} - \mathbf{B}\mathbf{B} + \frac{\mathbf{B}^2}{2}\overleftrightarrow{\mathrm{I}} + p\overleftrightarrow{\mathrm{I}} + \overleftrightarrow{\pi} \ , \tag{7}$$

where $\mathbf{B}$ is the magnetic field, $\vec{\vec{\mathrm{I}}}$ is the identity or unit tensor (unit dyad), p is the pressure, and $\vec{\vec{\pi}}$ is the viscous stress tensor ($p\vec{\vec{\mathrm{I}}}+\vec{\vec{\pi}}$ can also include the case with anisotropic pressure). With this $\vec{\vec{\Gamma}}$ the momentum (force balance) equation (1) takes the form

$$\rho\frac{d\mathbf{v}}{dt} = -\nabla p + \mathbf{j}\times\mathbf{B} - \mathrm{div}\vec{\vec{\pi}} + \mathbf{f} - \mathbf{v}S_\rho , \tag{8}$$

where

$$\frac{d}{dt} = \frac{\partial}{\partial t} + \mathbf{v}\cdot\nabla , \tag{9}$$

$\mathbf{j} = \nabla\times\mathbf{B}$ is the current density and

$$S_\rho = \frac{\partial\rho}{\partial t} + \mathrm{div}\rho\mathbf{v} . \tag{10}$$

Equation (8) covers a wide range of models. In the most simple case with $\vec{\vec{\pi}} = 0$, $\mathbf{f} = 0$ and $S_\rho = 0$ it gives a standard magnetohydrodynamic (MHD) equation for isotropic magnetically confined plasma without additional force sources and mass production. Effects of the plasma anisotropy and viscosity can be accounted for in (8) by keeping a symmetric tensor $\vec{\vec{\pi}}$, such as described in [12]. Then $\vec{\vec{\Gamma}}$ given by (7) is also symmetric.

At the moment we do not need to specify $\mathbf{f}$ and S_ρ. It is sufficient to note that $\mathbf{f}$ can contain the force on the plasma due to its interaction with the background neutral gas and/or the injected beam of neutral atoms. The term with S_ρ may represent the effects related to the plasma production/decay, for example, due to ionisation/recombination at the background gas, the pellet injection or gas puffing.

One can find an equation of motion in a form similar to (8) in a great number of papers, see, for example, [4] and references therein. In addition to the mentioned effects, relevant to contemporary fusion experiments, it can also contain the momentum transfer to the plasma due to the collisions with alpha particles, interaction with the charged dust particles and the gravity [13] (then $\mathbf{f} = \rho\mathbf{g}$ or $\mathbf{f} = -\nabla\Phi_{gr}$). Therefore, the validity of (8) is more general than the emphasized here for the toroidal systems with magnetic confinement such as tokamaks, stellarators and pinches.

With symmetric $\vec{\vec{\Gamma}}$ given by (7) equation (5) reduces to

$$T_\Gamma = T_R + T_{EM} + T_p + T_\pi , \tag{11}$$

where

$$T_R = -\int_S R\rho v_\zeta \mathbf{v}\cdot d\mathbf{S} \tag{12}$$

is the torque due to the Reynold stress $\rho\mathbf{vv}$,

$$T_{EM} = \int_V R\mathbf{e}_\zeta\cdot(\mathbf{j}\times\mathbf{B})dV = \int_S RB_\zeta\mathbf{B}\cdot d\mathbf{S} - \int_S R\frac{\mathbf{B}^2}{2}\mathbf{e}_\zeta\cdot d\mathbf{S} \tag{13}$$

is the electromagnetic torque due to Maxwell stress $\mathbf{BB} - \vec{\vec{\mathrm{I}}}\mathbf{B}^2/2$ (the electric field is ignored here, the conversion factor to SI units is $1/\mu_0$)

$$T_p = -\int_S Rp\mathbf{e}_\zeta\cdot d\mathbf{S} , \tag{14}$$

and

$$T_\pi = -\int_S R(\vec{\pi} \cdot \mathbf{e}_\zeta) \cdot d\mathbf{S} \tag{15}$$

is the viscous torque.

These general formulas, all expressed through the surface integrals, are a convenient basis for discussion of the integral torque balance (2), also containing T_f given by the volume integral (6). With definition (7), a part of T_f (or T_f itself) must be the torque T_{NBI} due to the neutral beams, which must be known in experiments.

The contributions (12)–(15) are completely determined by the plasma parameters at S, which means that these torques depend on the boundary conditions only. This is an important conclusion that points to the best strategy in calculations and experimental studies. It makes clear that a key to correct modelling must be adequate description of the quantities in the integrals (12)–(15) over the boundary S. The latter is not yet defined. Its definition becomes an essential part of the problem.

4. Analysis, reduction of general formulas, results and estimates

Equation (2) for the angular momentum L depends on the volume of integration in (3), (5) and (6). These and other integral relations above are valid for any V, but when we call it "plasma volume" the integrals (12)–(15) will be expressed through the physical quantities at the plasma boundary S_{pl}. Depending on experimental arrangements, S_{pl} is usually defined as sepratrix or the last closed magnetic surface. This means different structure of the magnetic field and different properties of the plasma in and out of S_{pl}.

The area around S_{pl} is a subject of intense dedicated studies on tokamaks [14, 15]. Accumulated knowledge is a perfect basis for prescribing the quantities in the surface integrals (12)–(15). However, for calculations it is tempting, as a first approximation, to assume sharp boundary plasma-vacuum. Such mathematically convenient model is very often exploited in theoretical studies of MHD equilibrium and stability [1]. Assuming vacuum outside S_{pl} would imply zero material fluxes through S_{pl}, while in real tokamaks they do exist and in no way can be disregarded. Such fluxes are a big problem for ITER as producing intolerable heat loads in the divertor [15].

With sharp plasma-vacuum boundary, or, more precisely, for a plasma that can be enclosed by a toroidal surface S where $\vec{\pi} = 0$ and $\rho = 0$, we immediately obtain $T_R = T_p = T_\pi = 0$. This reflects the fact that the internal forces cancel each other and do not produce the integral torque. On the other hand, it implies possible tremendous simplification in mathematics, if proper used.

This picture, being obviously unrealistic (no outward fluxes!), is, nevertheless, an indispensable step in theoretical modeling. It nullifies the other terms in (11), but allows an estimate of T_{EM} [16, 17]. Note that a nontrivial result for T_{EM} can be obtained only if there is a nonzero magnetic perturbation, while for an axially symmetric plasma equation (13) gives us $T_{EM} = 0$.

This can be easily shown in a general form. If $\mathbf{j}=0$ outside the plasma, the integration in (13) can be extended to a larger volume (for example, bounded by axisymmetric surface S_{as} in the vacuum) because a vacuum region with $\mathbf{j}=0$ does not contribute to T_{EM}. This choice can be done even for stellarators.

With axisymmetric surface S, the second term in (13) is zero, so that

$$T_{EM} = \int_V R\mathbf{e}_\zeta \cdot (\mathbf{j}\times\mathbf{B})dV = \int_{S_{as}} RB_\zeta \mathbf{B}\cdot d\mathbf{S}, \tag{16}$$

and T_{EM} is further simplified if $\mathbf{B}$ at S can be considered as a vacuum field. Indeed, representing $\mathbf{B}$ in the form

$$\mathbf{B} = \mathbf{B}_0 + \mathbf{b}, \tag{17}$$

where $\mathbf{b}$ is the perturbation and $\mathbf{B}_0$ is the axisymmetric part of $\mathbf{B}$ with natural $\mathrm{div}\mathbf{B}_0 = 0$ everywhere and $RB_{0\zeta} = \mathrm{const}$ in the vacuum, we reduce (16) to

$$T_{EM} = \int_{S_{as}} Rb_\zeta \mathbf{b}\cdot d\mathbf{S}. \tag{18}$$

Let us emphasize that this is an exact relation for the global electromagnetic torque on the plasma if S_{ax} is an axisymmetric surface in vacuum ($\nabla\times\mathbf{B}=0$ at S_{ax}).

It is interesting that in [3, 7, 9, 11, 14, 18], where “anomalous” or “unknown” torques have been discussed, the electromagnetic torque T_{EM} was not considered. Our analysis shows that, on the contrary, this must be the most “robust” contribution in a sense that we easily get nonzero T_{EM} in a general case [16, 17], while $T_{EM}=0$ only for ideal or perfectly symmetric plasmas.

The next question is how large can it be compared to other terms in (11) and to T_{NBI}. The estimates are easy: at normal component 5 G at the plasma surface and $2n/m=1$ equation (18) gives 0.2 N/m^2, which is comparable to the NBI torque density in DIII-D experiments [7, 9, 10]. However, even without numbers one can conclude from equations (11)–(15) that, at least in theory, T_{EM} must play a special role – as the only potential contribution to T in the model considered with S_{pl} as “plasma-vacuum”. As such, T_{EM} will also provide a scale for comparison at the next step of modeling with material interaction taken into account in the “vacuum” behind S_{pl}.

To find T_R, T_p and T_π, we have to incorporate the material fluxes through S. Here a theory should be based on the data from measurements at the plasma edge [3, 8, 10, 15, 19–21].

Assuming the bounding surface S axisymmetric ($\mathbf{e}_\zeta \cdot d\mathbf{S}=0$), we obtain $T_p=0$ in (14) irrespective of p at S and other geometrical details, which is the same as elimination of the term with $\mathbf{B}^2$ in (13). Also, $T_p=0$ if $p=\mathrm{const}$ at S (since $\mathrm{div}R\mathbf{e}_\zeta=0$). This justifies disregarding T_p in the global torque (11).

Direct calculations of the remaining T_R and T_π, given by (12) and (15), require information on $\rho v_\zeta \mathbf{v}\cdot\mathbf{n}$ and $(\vec{\pi}\cdot\mathbf{e}_\zeta)\cdot\mathbf{n}$, where $\mathbf{n}$ is the unit normal to S. We can also propose another way of finding $T_R + T_\pi$, which can be based on using experimental data for the scrape-off layer (SOL) plasma.

Consider the SOL region separated from the bulk plasma by S_{pl}, from outside by the outer magnetic surface S_{out} where we can put $\rho = 0$ and $\vec{\pi} = 0$, and from the divertor side by the cross-section S_{dt} of the divertor throat. Similarly to (2), we obtain for the SOL plasma

$$\frac{\partial L^{SOL}}{\partial t} = T_R^{SOL} + T_\pi^{SOL}, \tag{19}$$

where we disregarded the electromagnetic term and ignored T_p which is zero for axially symmetric boundary. Here T_R^{SOL} and T_π^{SOL} are given by (12) and (15), but now the boundary S consists of three parts: S_{pl}, S_{out} and S_{dt}, the latter connecting the inner and outer sides of S_{out} through the X-point and separating the SOL from the divertor area.

With $\rho = 0$ and $\vec{\pi} = 0$ at S_{out} these integrals over S_{out} are zero, the integrals over S_{pl} (with $d\mathbf{S}$ pointed into the plasma) are 'minus' T_R and T_π for the bulk plasma, and (19) reduces to

$$\frac{\partial L^{SOL}}{\partial t} + T_R + T_\pi = T_R^{SOL}(S_{dt}) + T_\pi^{SOL}(S_{dt}) \equiv T^{dt}, \tag{20}$$

where

$$T_R^{SOL}(S_{dt}) \equiv -\int_{S_{dt}} R\rho v_\zeta \mathbf{v} \cdot d\mathbf{S} \tag{21}$$

and

$$T_\pi^{SOL}(S_{dt}) \equiv -\int_{S_{dt}} R(\vec{\pi} \cdot \mathbf{e}_\zeta) \cdot d\mathbf{S}. \tag{22}$$

In a stationary state with $\partial L^{SOL} / \partial t = 0$ we obtain from (20)

$$T_R + T_\pi = T^{dt}. \tag{23}$$

With this relation the global torque balance (2) for the stationary plasma reduces to

$$T_{EM} + T^{dt} = -T_f. \tag{24}$$

Here we also used (4), (11) and $T_p = 0$.

To conclude the mathematical part, we remind that T_{EM} is given by (18),

$$T^{dt} = -\int_{S_{dt}} R(\rho v_\zeta \mathbf{v} + \vec{\pi} \cdot \mathbf{e}_\zeta) \cdot d\mathbf{S} \tag{25}$$

with $d\mathbf{S}$ pointed out (into the divertor), and T_f is the volume integral (6). The electromagnetic term can be calculated using any convenient axysymmetric toroidal surface S_{ax} enclosing the plasma. The term T^{dt} is determined by the plasma parameters at the divertor throat. Alternatively, the parts of T^{dt}, defined by (20), are given by the integrals (12) and (15) over the plasma surface S_{pl}.

Finally, analysis of the plasma rotation, considered in terms of the integral force balance, requires only careful description of its interaction with the "external world". It includes the neutral beams, the plasma behind the surface S_{pl} defined as "plasma boundary", and the magnetic filed produced by the currents outside S_{pl}. This means only two sources/sinks of the momentum in addition to the known one from NBI.

5. Discussion and proposals to theoretical studies and experiments

According to (24), in experiments with $T_f = T_{NBI}$ the counter torque must be $T_{EM} + T^{dt}$. This is a natural result obtained by integration of all possible contributions for a plasma described by (8) with $\mathbf{f}$ staying for the moment input from NBI.

In the absence of any auxiliary torque input, the integral torque balance in a stationary state reduces to

$$T_{EM} + T_R + T_\pi = T_{EM} + T^{dt} = 0 . \tag{26}$$

The both quantities in the second equality can be measured: the first as described in [16, 17] and the second by using the SOL or divertor data such as presented in [15, 19–21]. Such measurements could be an important step in studying the mystery of plasma rotation in tokamaks because (26) is the equation governing the intrinsic rotation.

According to definition (25), nonzero T^{dt} requires finite v_ζ at the divertor throat. Such flows are often observed in experiments [15, 19–21]. Therefore, $T^{dt} \neq 0$ is a natural expectation. Note that (26) is a general result which should cover all particular cases within the general model (8). Our analysis confirms that the line of studies [19–21]is the most promising. At the same time it shows that, for the torque balance evaluation, a theoretical model can sacrifice some minor details because the result (26) is determined by integration. Then the effects of ELMs, blobs, orbit losses, etc can be treated in terms of the averaged flux into the divertor. The same is also true for NTV studies such as [3, 7, 11] and mentioned therein.

An important consequence of (26) is that $T^{dt} \neq 0$ is coupled to $T_{EM} = -T^{dt}$. In a stationary state the electromagnetic torque T_{EM} (vanishing at $\mathbf{b} = 0$) is the result of plasma interaction with the error field $\mathbf{b}^{er}$, as implied by (18) with more details in [16, 17]. To give $T_{EM} \neq 0$, the plasma reaction $\mathbf{b}^{pl}$ must be with a phase shift relative to $\mathbf{b}^{er}$ [16, 17]. Such a shift, also a measurable quantity, comes from the plasma rotation and some dissipation inside. This rotation should be identified as the intrinsic rotation mentioned earlier.

If so, we come to the conclusion that this rotation is essentially related to the error field. This prediction could be easily verified in experiments if, simultaneously with $\mathbf{b}^{er}$ change (by the correction coils) the change in the momentum flow into the divertor would be measured. With $\mathbf{b}^{er}$ variation the intrinsic rotation subject to (26) must decrease if $|T^{dt}|$ increase slower than $|\mathbf{b}^{er}|^2$, increase in the opposite case or remain the same if $|T^{dt}| \propto |\mathbf{b}^{er}|^2$.

There is another interesting consequence of (26): with $T_{EM} = 0$ it gives $T^{dt} = 0$, which means, at $v_\zeta \neq 0$ at the divertor throat, absolutely asymmetric fluxes into the high- and low-field sides of the divertor. Reduction of the asymmetry of these flows with increase of $\mathbf{b}^{er}$ could be an indication of this tendency and another test of our predictions. For theory, $T^{dt} = 0$ or, equivalently, $T_R = -T_\pi$ shows that, in this case, the viscosity effects (due to NTV, for example) should not be considered separately from other contributions to the torque.

The presented theory is quite general. Somewhat approximate were only (19) with T_{EM} in the SOL region disregarded, and (20) with the flow through S_{out} assumed zero. The latter seems natural because the very idea of divertor is the wall protection. The plasma in SOL can freely flow along the magnetic lines. With $\mathbf{j}$ parallel to $\mathbf{B}$ we have no $\mathbf{j}\times\mathbf{B}$ force. The reaction of narrow-width resistive SOL plasma to $\mathbf{b}^{er}$ cannot be strong. Therefore, the approximations seem quite reasonable. The analysis shows that the intrinsic rotation can be explained by the asymmetry of fluxes into the SOL and by the plasma interaction with the error field.

References

[1] Progress in the ITER Physics Basis, Chapter 3, Nucl. Fusion **47** (2007) S128.

[2] GAROFALO, A. M., et al., "Stability and control of resistive wall modes in high beta, low rotation DIII-D plasmas", Nucl. Fusion **47** (2007) 1121.

[3] DeGRASSIE, J. S., "Tokamak rotation sources, transport and sinks", Plasma Phys. Control. Fusion **51** (2009) 124047.

[4] CALLEN, J. D., COLE, A. J., HEGNA, C. C., "Toroidal flow and radial particle flux in tokamak plasmas", Phys. Plasmas **16** (2009) 082504.

[5] SHAING, K. C., "Magnetohydrodynamic-activity-induced toroidal momentum dissipation in collisionless regimes in tokamaks", Phys. Plasmas **10** (2003) 1443.

[6] AYDEMIR, A. Y., "Shear flows at the tokamak edge and their interaction with edge-localized modes", Phys. Plasmas **14** (2007) 056118.

[7] SOLOMON, W. M., *et al.*, "Advances in understanding the generation and evolution of the toroidal rotation profile on DIII-D", Nucl. Fusion **49** (2009) 085005.

[8] SOLOMON, W. M., *et al.*, "Mechanisms for generating toroidal rotation in tokamaks without momentum input", Phys. Plasmas **17** (2010) 056108.

[9] SOLOMON, W. M., *et al.*, "Momentum confinement at low torque", Plasma Phys. Control. Fusion **49** (2007) B313.

[10] DeGRASSIE, J. S., *et al.*, "Intrinsic rotation in DIII-D", Phys. Plasmas **14** (2007) 056115.

[11] SOLOMON, W. M., *et al.*, "Momentum-Transport Studies in High ExB Shear Plasmas in the National Spherical Torus Experiment", Phys. Rev. Lett. **101** (2008) 065004.

[12] BRAGINSKII, S. I., "Transport processes in a plasma", Reviews of Plasma Physics, Vol. 1 (LEONTOVICH, M.A., Ed.) Consultants Bureau, New York (1965) 205.

[13] MIKHAILOVSKII, A. B., *et al.*, "Progress in Theory of Instabilities in a Rotating Plasma", Plasma Phys. Rep. **35** (2009) 273.

[14] Progress in the ITER Physics Basis, Chapter 2, Nucl. Fusion **47** (2007) S18.

[15] Progress in the ITER Physics Basis, Chapter 4, Nucl. Fusion **47** (2007) S203.

[16] PUSTOVITOV, V.D., "Electromagnetic torque on the toroidal plasma and the error-field induced torque", Nucl. Fusion **47** (2007) 1583.

[17] PUSTOVITOV, V.D., "The rotating wall effect on the error field induced torque and the error field shielding in tokamaks", Nucl. Fusion **49** (2009) 045003.

[18] DUVAL, B. P., *et al.*, "Bulk plasma rotation in the TCV tokamak in the absence of external momentum input", Plasma Phys. Control. Fusion **49** (2007) B195.

[19] LaBOMBARD, B., *et al.*, "Critical gradients and plasma flows in the edge plasma of Alcator C-Mod", Phys. Plasmas **15** (2008) 056106.

[20] GROTH, M., *et al.*, "Measurements and simulations of scrape-off layer flows in the DIII-D Tokamak", Journal of Nuclear Materials **390–391** (2009) 343.

[21] DeGRASSIE, J. S., *et al.*, "Intrinsic toroidal velocity near the edge of DIII-D H-mode plasmas", Nucl. Fusion **49** (2009) 085020.