Modelling of Rotating Plasma States and their Stability under the Influence of Helical Perturbations in TEXTOR and JET

A. Nicolai[1], **U. Daybelge**[2], **C. Yarim**[2]
[1]*Institut für Plasmaphysik, Forschungszentrum Jülich GmbH, Euratom Association, Trilateral Euregio Cluster, D-52425 Jülich, Germany*
[2]*Istanbul Technical University, Faculty of Aeronautics and Astronautics, 80626 Maslak, Istanbul, Turkey*
Email: A.Nicolai@FZ-Juelich.de

Abstract

The ambipolarity constraint and the parallel momentum equation of the revisited neoclassical theory allow to predict the parallel and poloidal flow speeds, $v_\parallel$, and v_Θ, respectively, and therefore the radial electric field E_r via the usual radial momentum balance equation.
The theory also accounts for the anomalous viscosity due to the plasma turbulence (ITG), the friction due to the recycled neutral gas, the momentum deposition due to NBI and due to a static or revolving helical perturbation field. A two time scale analysis allows to predict the stability of the asymptotic solutions, which depend on the initial values.

Key Words: Transport, Plasma Rotation, Perturbation Fields

Introduction

Anomalous plasma transport and the concomitant deterioration of the confinement times of tokamaks much below the neoclassical prediction, in particular if auxiliary heating is applied, are key issues in fusion research.
Therefore the surprising experimental discovery of the transition to a high confinement mode above a certain heating power has evoked considerable interest in improved confinement regimes.
The theory is valid in collision dominated plasmas with steep gradients and was able to reproduce the toroidal spin up in ALCATOR-C-MOD [1]. Here we concentrate on the influence of various source terms due to NBI, recycling and helical perturbation fields.

Plasma Rotation

The main result of the revisited neoclassical theory [1] is an equation describing the radial transport of toroidal momentum in a collisional subsonic plasma with steep gradients:

$$\frac{1}{\eta_2}\frac{\partial}{\partial r}[\eta_2(\frac{\partial g}{\partial r} - \frac{0.107q^2}{1+\frac{Q^2}{S^2}}\frac{\partial ln\,T}{\partial r}\frac{B_\phi}{B_\theta}h)] = \frac{\partial}{\partial t_T}g + T_{CX} + T_{NBI} + T_{ANI} + T_{j\times B} \qquad (1)$$

Here $t_T = \frac{t\hat{n}}{t_{ct}\hat{\eta}_2}$ is the normalized time used to evolve g (defined below). $T_{CX} = t_{ct}\frac{\hat{n}}{\hat{\eta}_2}\nu_{cx}g$ accounts for the friction caused by the neutral gas, $T_{NBI} = t_{ct}\frac{\hat{n}}{\hat{\eta}_2 v_T}\dot{v}_i$ for the momentum source due to neutral beam injection, $T_{ANI} = t_{ct}\frac{\hat{n}}{\hat{\eta}_2 \tau_{ani}}g$ for the braking of the velocity field due to pressure anisotropization evoked by helical perturbation fields and $T_{j\times B} = \alpha_{j\times B}t_{ct}\frac{v_T}{\delta_s}$ for the force density due to the $\vec{j}\times\vec{B}$ force at the singular layer. The reciprocal braking time [2] $\frac{1}{\tau_{ani}} = \frac{\sqrt{\pi}\,10^4\sqrt{T_i[eV]/A}}{R_0|m|}[\sum_{m,n}\frac{n^2 q}{|m-nq|}\frac{(B_{0,\theta}b_{\theta_{m,n}}+B_{0,\phi}b_{\phi_{m,n}})^2}{B_0^4}]$ accounts for the poloidal and toroidal components of the helical perturbation field, $b_{\theta_{m,n}}$ and $b_{\phi_{m,n}}$, respectively. The coefficient $\alpha_{j\times B} = \frac{nm_i 4\pi n^3 r}{\tau_s\beta_{fi}}\frac{\omega\tau_s}{(-\Delta')^2+(\omega\tau_s)^2}v_T$ with $\beta_{fi} = \frac{nm_i v_T^2 2\mu_0}{B_{hel}^2}$ accounts for the slip frequency ω between the the rotating plasma and the helical field, the radial component of which is B_{hel}. The quantities Δ', τ_s, δ_s are given [3]. The characteristic time t_{ct} at a point P_i (defined below) is given by $t_{ct}^{-1} = \frac{1}{m_j n_i L_\psi^2}\eta_{2i}$. m_j is the ion mass, n_i the ion density at P_i, $L_\psi = |(\frac{\partial ln\, T}{\partial r})_i^{-1}|$ the scale length of the ion temperature T at P_i. $x = \frac{r-r_i}{L_\psi}$ the radial coordinate, r_i the radius of P_i, and η_2 the perpendicular viscosity coefficient [1]. In the case of Alcator P_i was the 'inflexion' point of the temperature pedestal [1]. In the case of TEXTOR P_i is assumed to coincide with the plasma edge (r_i=r_s, r_s is the minor plasma radius). g and h are the normalized and poloidally averaged toroidal and poloidal velocities, $g = \int\frac{d\theta}{2\pi}\frac{u_\phi(\theta)}{v_T}$ $h = \int\frac{d\theta}{2\pi}\frac{u_\theta(\theta)}{v_T}$, respectively. v_T is the constant positive velocity $v_T = \frac{1}{eB_\phi}\frac{T_i}{L_\psi}$ [e is the elementary charge, $T_i = T(r_i)$]. B_ϕ is the toroidal field and B_θ the poloidal field. The velocities Q, S are defined in [1]. η_2 is the perpendicular viscosity. $\hat{n}$ and $\hat{\eta}_2$ are given below.

Combining the ambipolarity condition with the parallel momentum equation [1] we get in the case of large aspect ratio and circular cross - section an evolution equation for the poloidal plasma velocity.

$$(1+2q^2)\frac{\partial h^*}{\partial t_P} = -(h^*+1.833) + \{\frac{0.45\Lambda}{1+\frac{Q^2}{S^2}}\tilde{v}_T[-\frac{B_\phi}{B_\theta}]^2\{\frac{0.107q^2}{1+\frac{Q^2}{S^2}}h^* + \frac{1}{2}\frac{1}{[\frac{\partial\hat{T}}{\partial x}]^2}(g^*)^2$$

$$-\frac{1}{\frac{\partial\hat{T}}{\partial x}}g^*[h^* - (1+\frac{2}{\eta})] + 1.9[h^* - 0.8(1+\frac{1.6}{\eta})]^2\}\} \qquad (2)$$

Here the definitions $t_P = \frac{t}{t_{cp}}$, $t_{cp} = \frac{R^2\nu_j}{0.96v_{T_i}^2}$, $g^* = \frac{B_\theta}{B_\psi}g$, $h^* = \frac{u_\theta}{\tilde{v}_T}$ and $\eta = \frac{L_n}{L_T}$ with $\tilde{v}_T = \frac{T}{eB_\phi}\frac{\partial ln\, T}{\partial r}$ and $L_n = (\frac{\partial ln\, n}{\partial r})^{-1}$ are used, to cast equation (2) in a convenient form. The parameter Λ (crucial in the case of ALCATOR where finite Larmor radius effects are important) can be written as $\Lambda = \frac{\nu_j}{\Omega_j}\frac{q^2R^2}{L_T r}$. L_T is the radially varying decay length $L_T = (\frac{\partial ln\, T}{\partial r})^{-1}$. ν_j the ion - ion collision frequency, Ω_j the ion Larmor frequency, q the safety factor, R the major radius, $\hat{T} = \frac{T}{T_i}$ is the relative temperature, $\hat{n} = \frac{n}{n_i}$ the relative density and $\hat{\eta}_2 = \frac{\eta_2}{\eta_{2i}}$ the relative viscosity. Neglecting the time derivatives in (1) and (2) we obtain stationary equations [1] which are used in the next chapter exclusively. The characteristic time t_{cp} for the evolution of h^* is considerably smaller than t_{ct} for the evolution of g.

A two time step analysis, using an expansion with respect to $\frac{t_{cp}}{t_{ct}}$, allows to determine the dependence of the stability of the solution on the initial values [4].

Solution Method, Results and Discussion

The stationary equation (1) is a second order equation for g, the normalized toroidal velocity. This equation is replaced by two first order equations [1].
In addition we have the (stationary) equation (2) for the poloidal rotation. For a given temperature and density and normalized toroidal velocity g this equation is solved for h by means of a solver for transcendental equations. The boundary conditions are given in [1]. The viscosity η_2 accounts for the ITG - turbulence [1].
The input data are those of TEXTOR [1] and JET. The TEXTOR data are: $r_i = r_s$=46 cm, R=175 cm, T_{imax} = 1500 eV, T_{emax} = 1200 eV, n_{max} = 5.4 $10^{13}cm^{-3}$, η_i=1.6, B_ϕ = 2.23 T. NBI is charaterized by P_{MW} = 0.72, E_{keV} = 40 (deuterons). The plasma current is I_p = 351 kA.
Figs. 1 and 2 show the temperature profiles of TEXTOR [1] and JET (shot # 53298), respectively. Fig. 3 shows the toroidal speed for vanishing neutral gas density and Fig. 4 the analogous curve for n_0 = 4 $10^{16}m^{-3}$. Whereas in Fig. 3 the toroidal speed is too large by around 50 $\frac{km}{sec}$, in Fig. 4 the maximum toroidal speed $v_{\phi max}$ =110 $\frac{km}{sec}$ is reproduced with an accuracy of 10%. The ITG - turbulence accounts approximately for the enhancement of the classical momentum transport. The ratio of turbulent viscosity to the classical viscosity is around 100.
At the resonant surface which is located at the effective radius $\rho_{q=2}$ = 25 cm the toroidal velocity (Fig. 5) has a local minimum due to the braking term. Here it is assumed that the slip frequency vanishes i. e. the beam power and the rotation speed of helical field are adjusted to synchronize the plasma with the perturbation field.
At JET the large slip frequency ω prevented the penetration of the the helical field what is well described by $\alpha_{j\times B} \approx 0$. However, in the case of a synchronization (by AC - operation), the toroidal velocity profile of Fig. 6 could be obtained. The minimum is located at $\rho_{q=2}$ = 90 cm.

References

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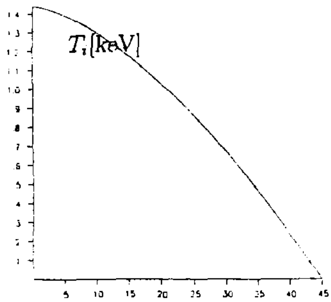


Fig. 1

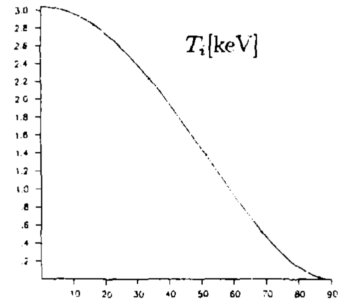


Fig. 2

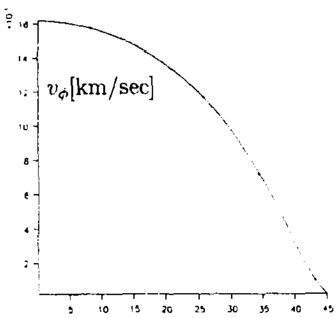
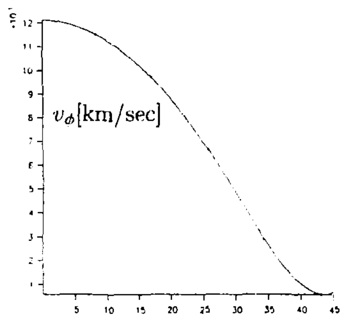


Fig. 3



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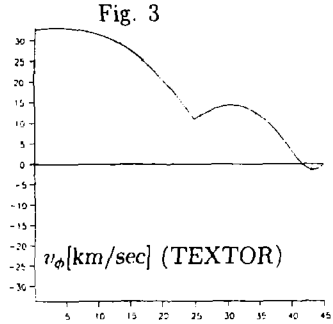

Fig. 5

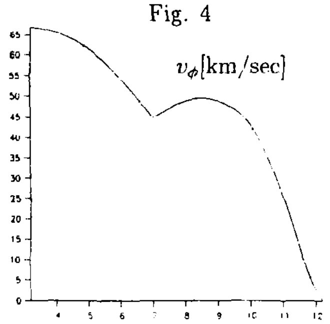

Fig. 6

Temperature profiles in TEXTOR and JET (Figs. 1, 2).
Toroidal velocity v_ϕ (TEXTOR) for $n_0 = 0$ and $n_0 = 4\ 10^{16} m^{-3}$ (Figs. 3, 4).
Toroidal velocity at synchronized operation (TEXTOR: Fig. 5, JET: Fig. 6).