

Simulations of the formation of a transport barrier in four channels including turbulent poloidal momentum, spinup

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Abstract

We have simulated the formation of a transport barrier on JET including a self-consistent treatment of ion and electron temperatures and poloidal and toroidal momentum. This has included an anomalous spinup of poloidal momentum similar to that in the experiment. We have used either the experimental profiles, with transport barrier, or artificial initial profiles, without barrier, as initial condition. The experimental density (with no barrier) was used and kept fixed. The result was that barriers, or spinup, developed in all channels with profiles close to the experimental. Note that there is no free parameter in the code but the uncertainty in Z_{eff} has been used for adjustments. The barrier develops at a region with small magnetic shear outside the main deposition of energy. The physics of the poloidal spinup was the development of zonal flows. For the toroidal momentum pinch the symmetry breaking effect of toroidicity was dominant.

Introduction

The understanding of the formation of transport barriers is presently one of the outstanding issues in fusion transport research¹⁻⁸. This problem area consists of several parts including the separate dynamics of poloidal and toroidal momentum, effects of field ripple at the edge, magnetic q profile and several other issues. The most striking new feature observed is that of the poloidal momentum spinup³. This has been found to give rotation of up to an order of magnitude larger than the neoclassical rotation. We will here show how such poloidal spinup, which requires a poloidal momentum pinch, can result from Zonal flows generated by drift wave turbulence. Results consistent with the JET barrier pulses 58094 and 69454 have been obtained but similar spinup was also obtained for the barrier shot 51976 (no experimental poloidal rotation measurements available).

Formulation

For the toroidal momentum transport we use the recently derived toroidal symmetry breaking effects⁷. Adding electromagnetic effects to the formulation in Ref 7 we get:

$$m_i N_i \left(\frac{\partial}{\partial t} + 2\vec{U}_{Di} \cdot \vec{\nabla} \right) \delta u_{\parallel} = -m_i N_i \bar{u}_E \cdot \nabla U_{\parallel 0} - \left[\hat{e}_{\parallel} \cdot \nabla + U_{\parallel 0} \frac{m_i \vec{U}_{Di}}{T_i} \cdot \nabla \right] \left(\delta p_i + e N_i \phi - \frac{\omega + \omega_{*e}(1 + \eta_e)/\tau}{k_{\parallel} c} A_{\parallel} \right) \quad (1a)$$

$$\delta u_{\parallel} = -\frac{k_{\theta} D_B}{\omega - 2\omega_{Di}} \frac{dU_{\parallel 0}}{dr} + \frac{\langle k_{\parallel} \rangle + \omega_{Di} U_{\parallel 0} / (\tau \cdot c_s^2)}{\omega - 2\omega_{Di}} \left(\delta p + ne\phi - \frac{\omega + \omega_{*e}(1 + \eta_e)/\tau}{k_{\parallel} c} A_{\parallel} \right) / (m_i n_i) \quad (1b)$$

$$\vec{U}_{Di} = 2 \frac{c T_i}{e B^2} \hat{n} \times \nabla B; \quad \Gamma_{\parallel} = \langle v_{Er} \delta u_{\parallel} \rangle \approx \Gamma_{\phi} \quad (1c)$$

Here the convective magnetic drift term in the left hand side can either be obtained from a gyrofluid approach^{6,9} or from fluid equations including the stress tensor^{7,8}. The first term on the right hand side is the ExB convection in the background velocity gradient. This gives the diagonal element. Using the saturation level:

$$\frac{e\phi}{T_e} = \frac{\gamma}{k_{\theta} c_s k_r \rho} = \frac{\gamma}{\omega_{*e} k_r L_n} \quad (2)$$

we then get the diagonal element :

$$\chi_{\phi} = \frac{\gamma^3 / k^2}{(\omega_r - 2\omega_{Di})^2 + \gamma^2} \quad (3)$$

It is important to note, however, that this diagonal element is not uniquely defined. The reason is that it depends on the frequency which, in turn, depends on all other gradients in the system through the dispersion relation.

The poloidal flux is given by the Reynolds stress as:

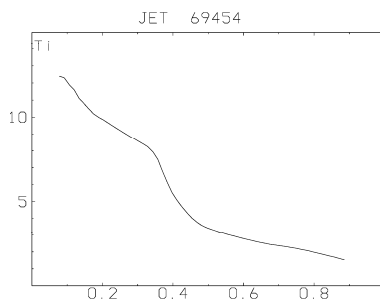
$$\Gamma_p = \langle v_{Er} v_{\theta} \rangle = -D_B^2 k_r k_{\theta} \frac{1}{2} \hat{\phi}^* \left[\hat{\phi} + \frac{1}{\tau} \hat{P}_i \right] + c.c \quad (4)$$

Here also the diamagnetic drift was included as a convected velocity

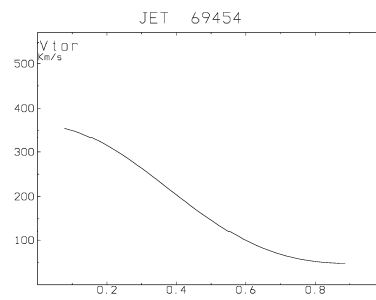
Simulations

We have simulated the JET shots 58094, 51976 and 69454. All of these give a strong spinup of the poloidal rotation in the simulations. However experimental data on poloidal rotation is missing for 51976. We here show the barrier formation in 69454.

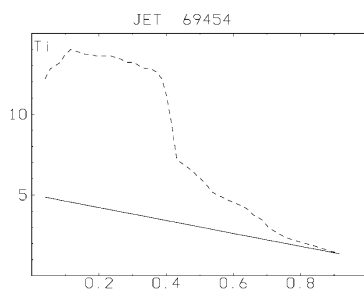
Experimental Ti



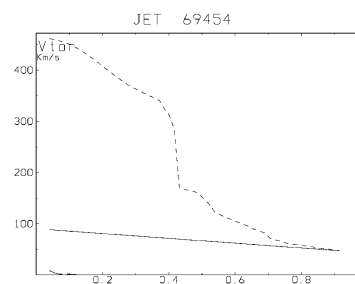
Experimental Vtor



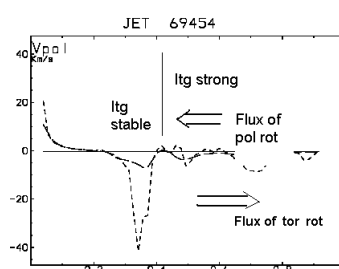
Simulated Ti (dotted)
Initial profile (full)



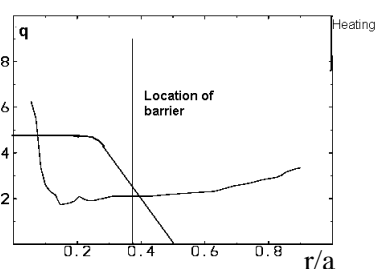
Simulated Vtor (dotted)
Initial profile (full)



Simulated poloidal spinup (dotted)
Neoclassical rotation (dashed)
Initial condition (full)



The experimental poloidal spinup has the same location and magnitude (40 km/s) but was measured on impurities and therefore had the opposite direction in this case. The net poloidal flux is indicated as inward in the picture but is in the end zero when it is balanced by outward flux from the enhanced piled up rotation since there is no poloidal momentum source. The net toroidal momentum flux is outward in equilibrium since there is a torque deposition in the interior. There is, however, a strong inward component of the toroidal flux which enhances the inward peaking. We notice that the simulated profiles have somewhat more pronounced barriers (in particular Vtor) but the central values are quite similar to the experimental. There was no trace of the barrier in the initial conditions. The ITG mode is stable within the barrier while the Trapped electron mode is marginally unstable. The toroidal rotation continues to grow towards the axis inside the barrier because of the torque deposition. When there is no barrier there is no poloidal spinup. In these cases the poloidal momentum flux fluctuates in both time and space. The location of the barrier is due to a combination of small magnetic shear and the power deposition profile.



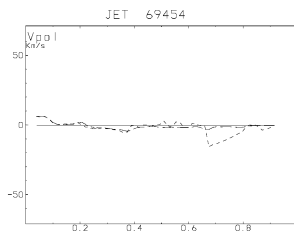
Picture showing that the main power deposition is inside the location of the barrier (at 0.4) while magnetic shear is still small

Electromagnetic effects

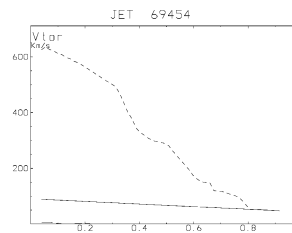
We recently discovered that electromagnetic effects have a significant influence on the momentum transport. This enters through the toroidal momentum¹⁰ but also influences

poloidal momentum. In fact, there is no pronounced barrier and no poloidal spinup in the electrostatic limit.

Electrostatic Pol rot



Electrostatic Tor. rot



Discussion

We have shown how a fluid model containing both poloidal and toroidal momentum transport can describe the formation of a transport barrier in a selfconsistent simulation of four channels, ion and electron temperature and poloidal and toroidal momenta. The poloidal spinup has previously been recovered also for JET51976 and JET58094 although experimental measurements of the poloidal rotation are missing for 51976. The barrier location is here a result of small magnetic shear (optimized shear) and the power deposition. Rotation is driven by the temperature scale length and this requires both large thermal flux and an additional mechanism which limits transport so that the scale length is reduced. The Trapped Electron mode dominates transport in the whole region of small and negative magnetic shear. However, the ITG mode would also be unstable in the absence of flowshear. Since this model does not include transport driven by electromagnetic effects it is not sensitive to exact values of magnetic q (like rationals). The convergence of the results with respect to resolution has been tested with almost the same results between 50 and 99 radial gridpoints. We have also tested results in the electrostatic limit and in the absence of electron trapping. No barrier is formed in these cases. In particular electromagnetic effects have recently been found to be important for the toroidal momentum pinch¹⁰. This opens up a possible explanation for the stronger barrier in the simulation. The model for elongation is rather crude and usually underestimates the effect. Elongation acts as to reduce electromagnetic effects which, in turn, tend to increase the toroidal momentum pinch. Thus a stronger effect of elongation is expected to reduce the momentum pinch.

References

1. J.E. Rice, E.S. Marmor, F. Bombarda and L. Qu, Nuclear Fusion **37**, 421 (1997).
2. P.C. deVries, K.M. Rantamäki, C. Giroud, E. Asp, G. Corrigan, A. Eriksson, M. deGreef, I. Jenkins, H.C.M. Knoop, P. Mantica, H. Nordman, P. Strand, T. TALA, J. Weiland, K-D Zastrow and the JET-EFDA contributors, Plasma Phys. Control. Fusion **48**, 1693 (2006).
3. K. Crombe, Y. Andrew, M. Brix et. al. Phys. Rev. Lett. **95**, 155003 (2005).
4. J. Weiland and H. Nordman, Proceedings of the 33rd EPS conference, Rome 2006, ECA Vol. 301, P-2, 186.
5. T. Tala, K-D. Zastrow, J. Ferreira et.al. Phys. Rev. Lett **102**, 075001 (2009).
6. T.S. Hahn, P.H. Diamond, O.D. Gurcan and G. Rewoldt, Phys. Plasmas **14**, 072302-1 (2007).
7. J. Weiland, R. Singh, H. Nordman. P.K. Kaw, A. Peeters and D. Strintzi Nuclear Fusion **49**, 065033 (2009).
8. D. Strintzi, A.G. Peeters and J. Weiland, Phys. Plasmas **15**, 044502 (2008).
9. R.E. Waltz, R.R. Dominguez and G.W. Hammett, Phys. Fluids **B4**, 3138 (1992).
10. A. Mahmood, A. Eriksson and J. Weiland, *Electromagnetic effects on toroidal momentum transport*, Submitted to Physics of Plasmas.