33rd EPS Conference on Plasma Phys. Rome, 19 - 23 June 2006 ECA Vol.**30I**, P-1.097 (2006)

Momentum transport in the MAST spherical tokamak

M. Wisse[1], R. J. Akers, N. J. Conway, A. R. Field, P. Helander, S. Newton[2]

EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK

[1] University College Cork, Cork, Ireland

[2] University of Bristol, H. H. Wills Physics Laboratory, Royal Fort, Tyndall Avenue, Bristol, BS8 1TL, UK

Introduction

Extrapolation of the confinement of current tokamaks to ITER conditions relies on our ability to predict the level of cross-field transport. For this it is necessary to understand the processes controlling plasma rotation and momentum transport because sheared flow can influence the level of anomalous transport. Sheared ExB flow can reduce the level of anomalous transport through the radial de-correlation of turbulence and is one of the factors that is involved in the formation of internal transport barriers (ITBs) [1, 2]. Although particle and heat diffusivities down to the underlying ion neoclassical level have been observed in ITB plasmas [2,3], the momentum diffusivity has always remained anomalous. According to neoclassical theory, because trapped particles do not transport angular momentum, the momentum diffusivity should be smaller than the ion heat diffusivity by a factor $O(\varepsilon^{3/2})$, where ε is the inverse aspect ratio. However, experimentally, the momentum diffusivity is usually found to be of the same order as the heat diffusivity [4]. Recent enhancements to neoclassical theory [5] predict an increase of momentum transport in a mixed collisionality plasma in the presence of strong toroidal rotation. The additional transport is driven by pressure and temperature gradients rather than rotational shear and therefore cannot be expressed in terms of a simple diffusivity. The level of neoclassical transport is calculated here using this theory for a MAST spherical tokamak [6] L-mode plasma and compared with the experimentally determined fluxes. The test of the the theory is made easier because the tangential NBI heating drives strong toroidal rotation in MAST.

Neoclassical transport

Cross-field fluxes of particles, heat and angular momentum are related to the gradients of pressure, temperature and rotation frequency through the transport matrix, L_{ij}:

$$\begin{pmatrix}\Gamma\\ q\\ \Pi\end{pmatrix} = -\begin{pmatrix}L_{11} & L_{12} & L_{13}\\ L_{21} & L_{22} & L_{23}\\ L_{31} & L_{32} & L_{33}\end{pmatrix}\begin{pmatrix}\partial_r \ln p\\ \partial_r \ln T\\ \partial_r \ln \omega\end{pmatrix}$$

where Γ is the particle flux, q the heat flux, Π the angular momentum flux and p, T and ω are pressure, temperature and toroidal angular velocity of the bulk ions respectively. The transport coefficients resulting from collisional transport, consisting of both a classical contribution due to the particle gyromotion and a neoclassical contribution due to guiding centre drifts in a toroidal plasma, have been derived theoretically with increasing levels of sophistication. In particular, the influence of impurities and toroidal rotation on the heat and particle transport have been considered by Fülop and Helander, who calculated the particle and heat transport for a mixed collisionality plasma with strong rotation [14], which is typical for MAST plasmas. This theory has recently been extended by Newton and Helander to include momentum transport as well [5]. In a strongly rotating plasma, the centrifugal force causes ions to distribute non-uniformly around a flux surface [15] and this effect is most pronounced for impurity ions, due to their larger mass. The density asymmetry, which is balanced by an electrostatic potential that is set up around the flux surfaces, enhances the friction between ions and impurities, leading to enhanced transport. The density of an ion species is given by $n_i = n_{i,0}exp(M_i^2-z_i\varphi/T_i)$, and that of the electrons by $n_e = n_{e,0}exp(\varphi/T_e)$, where $n_{i,0}$ is the density on the outboard mid-plane, z the charge, φ the potential relative to the outboard midplane, T the temperature in eV. M_i^2 is defined to be $m_i\omega^2(R^2-R_0^2)/2eT_i$, where m_i is the ion mass, ω the angular velocity, R the radius and R_0 the outboard mid-plane radius of the flux surface. The set of equations is closed by imposing quasi-neutrality: $\Sigma n_i z_i = n_e$.

Calculating the neo-classical transport

The plasma parameters required to calculate the transport from theory are measured on MAST using state-of the-art diagnostics covering the full plasma diameter, including a high-resolution Thomson scattering system providing T_e and n_e profiles [8, 9], a 2D visible bremsstrahlung diagnostic providing Z_{eff} profiles [10] and a high resolution charge exchange diagnostic measuring ion temperature and toroidal rotation velocity profiles [11]. The raw measurement data is prepared in an integrated way for transport analysis using the TRANSP transport analysis code [7,13]. This pre-processing accounts for inter-dependencies of the measurement data, e.g. the evaluation of Z_{eff} requires T_e and n_e profiles, and spatial mapping of profiles to the magnetic equilibrium from EFIT [17]. The actual transport fluxes determined from TRANSP can then be compared with the neo-classical predictions.

The expressions for the transport coefficients include flux surface averages involving, e.g. density and magnetic field strength. It is assumed that the sole impurity is C^{6+}. On MAST, the bulk ions are deuterium. The bulk and impurity ion densities around the flux surfaces are calculated from the above set of equations using the electron density and the Z_{eff} profile. In principle the densities can be derived by solving the above equations by, for example, a Newton or Broyden method. However, these methods were found to be unsuitable in practice and so an analytic approximation was used to interpolate between the two cases for which the set can be solved exactly, i.e. the cases of a deuterium plasma with a trace amount of carbon, and a carbon plasma with a trace amount of deuterium. The electrostatic potential can then be expressed as $\varphi = (M_D^2+\gamma M_C^2) / (1+\tau+\gamma(z_C+\tau))$, where $\gamma = z_C n_C/n_D$ and $\tau = T_i/T_e$. The bulk and impurity ion temperature are assumed equal, as is also assumed in the theory. Further necessary conditions for validity of the theory are that the square of the toroidal Mach number of the bulk ions, $m_D\omega^2R^2/2kT_D$, is smaller than 1, and that the temperature and density gradient scale lengths are longer than the ion Larmor radius.

Results

The results described below are for an L-mode discharge (#12546, 0.245 s, I_p=0.7MA, B=0.5T, $n_D=3.6\cdot10^{19}m^{-3}$, NBI=1.5MW co, Z_{eff}=1.5-4.5). The carbon ion Mach number, $m_c\omega^2R^2/2kT_c$, was found to be 0.5 and the density and temperature gradient scale lengths were 10 times the deuterium Larmor radius, which means that the transport equations are valid. Fig 1 shows the normalized transport coefficients (ie. number of units of flux per unit gradient) for each of the driving forces ∇p, ∇T and $\nabla\omega$, as well as the predicted and measured diffusion coefficients $D = -\Gamma/\nabla n$, $\chi_i = -q/n\nabla T$ and $\chi_\varphi = -\Pi/nmR^2\nabla\omega$, the experimental one being determined from the fluxes found by TRANSP, and the predicted one from the fluxes predicted by neoclassical theory. The spike in fig (1a) is due to a sign

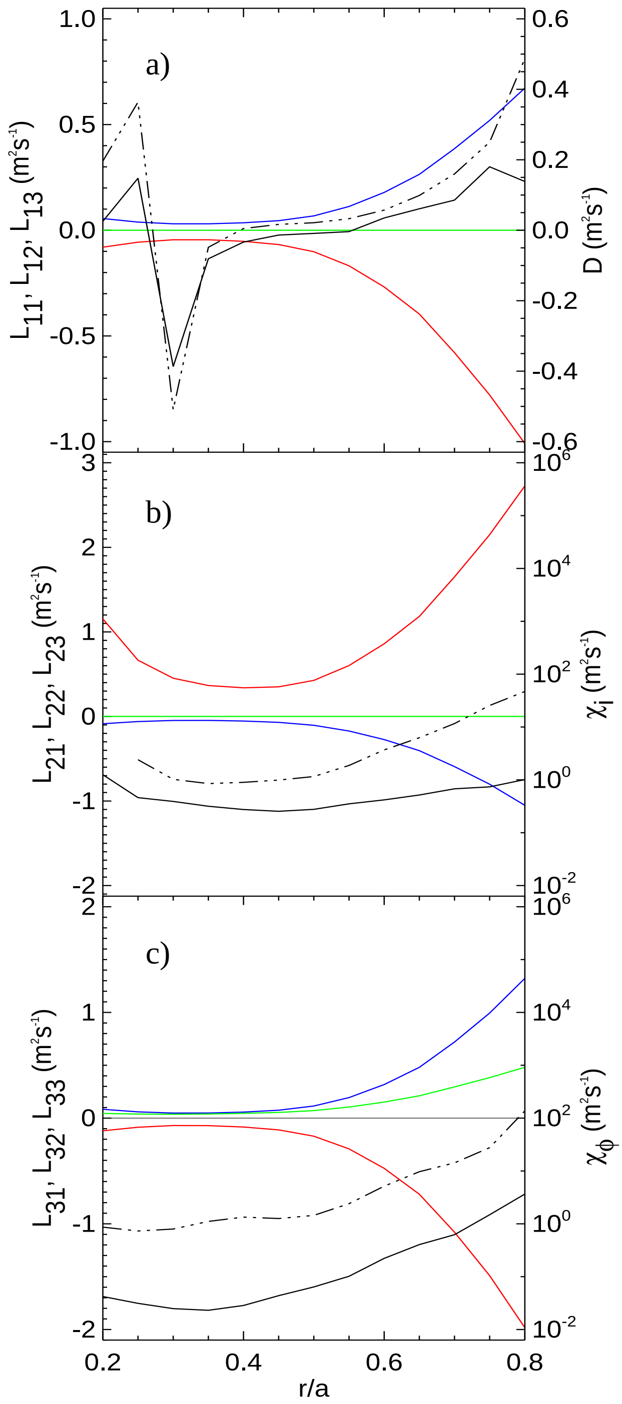

Fig 1: Normalized transport coefficients corresponding to pressure (blue), temperature (red) and velocity (green) gradients, left scale, and TRANSP (dot-dash) and predicted (solid black) particle, heat and momentum diffusion coefficients, right scale.

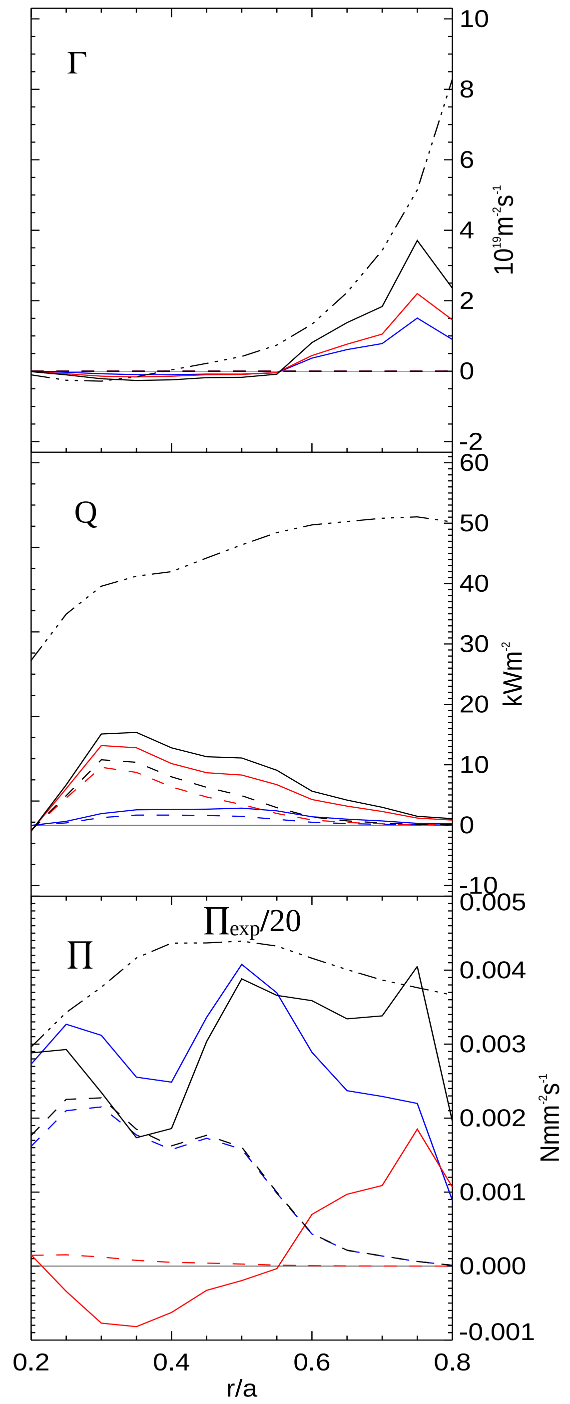

Fig 2: Classical (blue), neoclassical (red) and total (black) particle, heat and angular momentum flux with (solid) and without (dashed) including carbon, and the TRANSP value (black dot-dash), divided by 20

reversal of the density gradient. Since the gradients in a tokamak are typically negative, it is seen from fig 1 that the density gradient drives an outward particle and angular momentum flux, but an inward heat flux, whereas the temperature gradient drives an inward density and angular momentum flux, but an outward heat flux. Velocity shear does not contribute to a particle or heat flux, but drives an outward angular momentum flux. The transport coeficients increase towards the edge, because both the classical and neoclassical transport scale with Z_{eff}. Fig 2 shows the predicted classical and neoclassical fluxes, their sum, and the measured fluxes, and makes a comparison between the case where carbon is included in the calculations, and where it is not. It is seen from fig 2 that in the absence of impurities, there is no particle transport driven by gradients, a well known result. Including impurities leads to an increased friction of particles on neighbouring flux surfaces, which enhances both the classical fluxes and the neoclassical fluxes. The heat flux is increased by a factor between 2 and 20, but remains well below the experimental value. This means that the L-mode ion heat confinement time is not neoclassical, as one would expect. Increased friction causes a significant enhancement of both the classical and neoclassical parts of the angular momentum flux. The enhancement of the classical flux varies between a factor of 1.5 in the core up to 100 in the edge, and the neoclassical flux increased by as much as four orders of magnitude in the edge. Nevertheless, the total angular momentum flux remains about a factor of 25 below the experimental value for this L-mode discharge. Due to the similarity of the pressure and temperature profiles, both the classical and neoclassical contributions to the angular momentum transport due to the pressure and temperature gradients (L_{31} and L_{32}) almost cancel throughout the plasma. In addition, the neoclassical contribution driven by the velocity shear (L_{33}) is almost zero, as it scales with the square of the bulk ion Mach number, leaving the classical part of L_{33} as the main source of the angular momentum flux. The next step will be to apply this analysis to discharges with moderate to strong ITBs, where the off-diagonal terms may play a bigger role.

References

[1] R. C. Wolf, Plasma Phys. Control. Fusion **45** (2003) R1

[2] A R Field , The MAST Team, R Akers, C Brickley, P Carolan, N Conway, G Cunningham, H.Meyer, M Walsh , C Challis, *Transport in the presence of ITBs in the MAST Spherical Tokamak*, P4.190, 31st EPS Conference on Plasma Physics, London, 28th June-2nd July 2004.

[3] C. M. Greenfield, C. L. Rettig, G. M. Staebler et al, Nucl. Fusion **39** (1999) 1723.

[4] J. E. Rice, W. d. Lee, E. S. Marmar et al, Nucl. Fusion **44** (2004) 379.

[5] S. Newton, P. Helander, Physics of Plasmas **13** 012505 (2006)

[6] A. C. Darke et al 1995 Proc. 18th Symp. on fusion Technology (Karlsruhe, Germany, 22-26 August 1994) vol 1 (Amsterdam: Elsevier) 799.

[7] R. J. Akers et al, Plasma Phys. Control. Fusion **45** (2003) 175.

[8] M. J. Walsh et al, Rev. Sci. Inst. **74**, No 3 (2003) 1663.

[9] M. J. Walsh et al, Rev. Sci. Inst. **70**, No 1 (1999) 742.

[10] A. Patel et al, Rev. Sci. Inst **75**, No 11 (2004) 4944.

[11] N. J. Conway, M. Wisse, R. J. Akers, C. Brickley, P. G. Carolan, A. R. Field, M. J. Walsh, *Transport studies in MAST with enhanced Doppler spectrometry*, P4.100, 32nd EPS conference on plasma physics, Tarragona, 27th June–1st July 2005.

[13] A. Pankin, D. McCune, R Andre et al, Computer Phys Comm. **159** 3 (2004) 157-184

[14] T. Fülop and P. Helander, Phys. Plasmas **6** (1999) 3066.

[15] J. A. Wesson, Nucl. Fusion **37** (1997) 577.

[16] S. I. Braginskii, JETP (USSR) **6** (1958) 358.

[17] L.L. Lao, Nuclear Fusion **25** (1985) 1611.

The authors would like to acknowledge D. McCune for helpful comments regarding TRANSP.

This work was funded jointly by the United Kingdom Engineering and Physical Sciences Research Council and by the European Communities under the contract of Association between EURATOM and UKAEA. The views and opinions expressed herein do not necessarily reflect those of the European Commission.