Role of turbulence regime and ExB shear upon particle transport in DIII-D H-mode plasmas

S. Mordijck 1), L. Zeng 2), L. Schmitz 2), E.J. Doyle 2), W-H. Ko 3), X. Wang 1), T.L. Rhodes 2), G. Staebler 4), P.H. Diamond 5), B. Grierson 6), G.R. McKee 7), C.C. Petty 4), A. Salmi 8), W. Solomon 6), T. Tala 8) and the DIII-D team

1) The College of William and Mary, Williamsburg, Virginia, 23187, USA.
2) University of California – Los Angeles, Los Angeles, California, 90095, USA.
3) KSTAR, National Fusion Research Institute, Daejeon, 305-806, Korea.
4) General Atomics, P.O. Box 85608, San Diego, California, 92186-5608, USA.
5) University of California - San Diego, San Diego, California, , USA.
6) Princeton Plasma Physics Laboratory, Princeton, New Jersey, 08543-0451, USA.
7) University of Wisconsin, Madison, Wisconsin, 53806, USA.
8) VTT, Espoo, Finland.

Email contact of main author: mordijck@fusion.gat.com

Abstract. Particle confinement in H-mode plasmas on DIII-D is strongly affected by the turbulence regimes as well as the ExB shearing rate. We observe a strong increase in particle transport when the plasma transitions from an Ion Temperature Gradient (ITG) regime to a Trapped Electron Mode (TEM) regime by changing the heating from Neutral Beam Injection (NBI) to Electron Cyclotron Heating (ECH). The theoretical increase in particle transport is driven by an increase in outward particle flux outside the mid-radius, as calculated with the trapped gyro-Landau fluid model TGLF. This is due to a switch in the turbulence group velocity from the ion to the electron direction. Perturbed experimental particle transport coefficients confirm the strong increase in outward diffusion outside $\rho = 0.6$. We also observe a strong increase in density fluctuations at the TEM scale-length in the plasmas with ECH heating. We were able to limit the density reduction in these ECH heated plasmas, by changing the torque input, in order to increase the ExB shearing rate. We find that the plasmas with the best particle confinement in the TEM regime are those in which the ExB shearing rate is of similar strength or exceeds the linear growth rate. One interesting observation is that in the plasmas in which we observe a strong increase in TEM scale density fluctuations, we also observe a strong increase in the inward convection at the same radial locations.

1. Introduction

In order to achieve a high fusion gain in future magnetic confinement devices, we need a high plasma density. Currently, we do not have a predictive capability to determine the density profiles in future devices and experiments [1]. The core density profile in ITER is considered to be flat and changes to this prediction will affect the bootstrap current and impurity accumulation in the plasma core. On the other hand, Angioni et al. [2] showed that there is an inverse correlation between collisionality and density peaking in the plasma core, i.e. density peaking increases at lower collisionality. However, self-similar experiments on DIII-D (in L- and H-mode) and JET (only in L-mode) have shown that there is no relationship between density peaking and collisionality, if only the collisionality is varied [3,4]. In JET H-mode plasmas, similarly to the results in AUG, an increase in density peaking is observed with collisioanlity [2,4]. Thus the current focus on changes in particle transport concentrates on the changes in turbulence and the changes in toroidal rotational shear [5,6].

In this paper we will show that the changes in turbulence regime from dominant ITG to TEM result in an increase in outward particle flux (section 2) and that when the ExB shear is larger than the linear growth rate, particle confinement improves (section 3). We find that in the TEM dominant plasmas there is an increase in experimental density fluctuations at the intermediate scale. Moreover, the outward modeled turbulent particle flux outside ρ=0.6, is in agreement with experimental observations of the perturbed transport coefficients. These perturbed transport coefficients show also a strong increase in particle transport outside the mid-radius. In the second part of the paper, we will show that particle confinement can be improved by increasing the ExB shear in comparison to the linear growth rates. We observe that density peaking does not correlate with changes in toroidal rotational shear, u'. However the ExB shear plays a critical role in determining particle confinement. In the discussion (section 4) we will compare these results with previous work on other tokamaks and existing theories.

2. Role of turbulence regime

In order to change the turbulence regime in a set of low power (3-4 MW), low density (2-4 $\times 10^{19}$ m^{-3}) H-mode plasmas, we changed the heating power from NBI to ECH. We kept the torque input close to zero in both the ECH and the NBI heated discharges (between 0-0.5N-m). We were able to vary the Te/Ti (electron temperature/ion temperature) from 0.7-2.0. This allows us to switch from a dominant Ion Temperature Gradient (ITG) to a dominant Trapped Electron Mode (TEM) regime, see Fig. 1. Theory predicts that an outward particle flux results from changing the turbulence group velocity from the ion to the electron direction. We find that the TEM-dominant plasmas have a strong overall reduction in plasma density across the density profile (see [Fig. 2(a)]. The NBI heated plasma is more peaked inside ρ = 0.3, which is the result of fueling of the core with the neutral beams in comparison with the ECH heated discharges, where core fueling is strongly reduced. A particle balance shows, that this reduction in core fueling cannot explain the overall change in the density profile [7]. A modification in particle transport is needed to explain the changes in the gradients as well as the overall reduction of particle confinement.

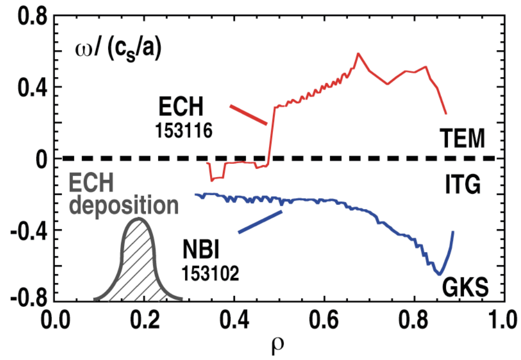

Fig. 1. Frequency of largest linear growth-rate shows that the ECH heated plasmas transition to a TEM unstable regime close to mid-radius, whereas the NBI heated plasmas remain ITG unstable using GKS.

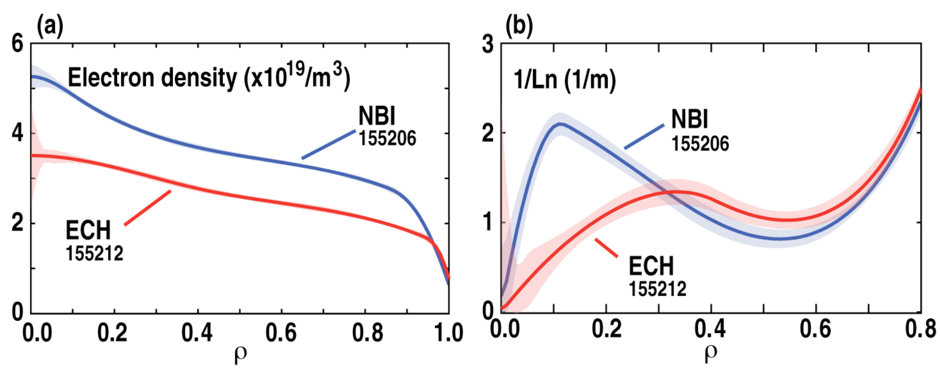

Fig. 2. a) Electron density fit based on reflectometer data shows a strong reduction in overall density when ECH is applied. b) The density in the NBI heated discharge peaks in the core, due to core fueling from the beams, whereas the ECH heated plasmas have a larger density gradient outside ρ=0.3.

In order to assess how particle transport changes, we applied a perturbative gas puff. This results in a modulation of the density profile with a fixed frequency. By fitting this perturbation, we can extract the amplitude and phase of this modulation at each radius, by using the reflectometer.

Takenaga et al. [8] derived expressions for D, the diffusion coefficient and v, the inward pinch as a function of the amplitude and phase of a perturbed density profile. This technique has been successfully applied in DIII-D H-mode and L-mode plasmas, as well as on JET [3,9,10]. Using this technique we find that the outward diffusion as well as the inward pinch is affected by changing turbulence regimes, see [Fig. 3(b)]. We find that just outside mid-radius the increase in outward diffusion is countered by a strong increase in inward pinch in the TEM unstable plasmas. Outside ρ = 0.6, the inward pinch goes back to values of the ITG unstable plasmas and with the strong increase in outward diffusion this leads to a strong increase in outward transport, as expressed by v/D. TGLF simulations [11] show qualitative agreement with this experimental observation, see [Fig. 3(a)]. At ρ=0.5 there is a shift to higher $k_\theta\rho_s$ for the TEM unstable plasma, but the integrated turbulent particle flux is very similar to the ITG unstable plasma. Only further out, at ρ=0.74, not only has the peak flux shifted to higher $k_\theta\rho_s$, but the integrated flux has increased in the TEM unstable discharges. These theoretical calculations are in agreement with experimental observations of changes in particle transport. However the TGLF calculations do not differentiate between the inward pinch and outward diffusion and just give the overall normalized particle flux.

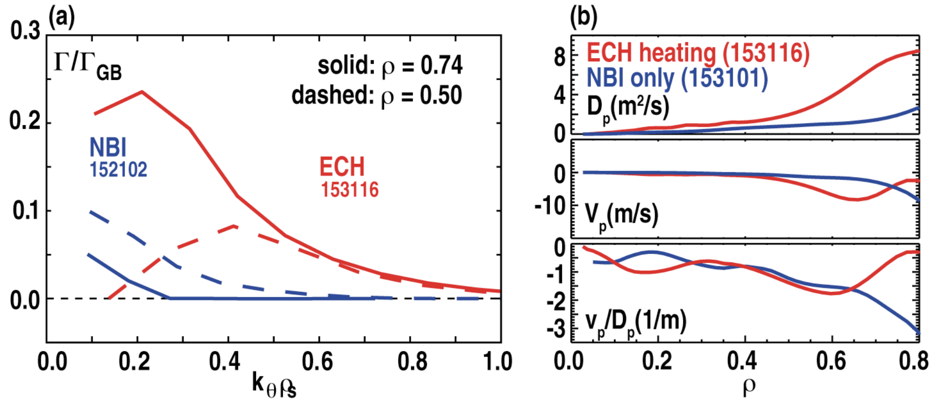

Fig. 3. a) TGLF calculations of the normalized particle flux at two radial locations shows a strong increase in particle transport for the ECH heated plasma outside mid-radius. b) Experimental perturbed D,v and v/D transport coefficients obtained by adding a perbative gas puff.

We observe a strong increase in density fluctuations at the intermediate scale as measured with the Doppler BackScattering (DBS) [12,13] in the TEM dominant plasmas in comparison with the ITG dominant plasmas, see Fig. 4. The linear growth rates at intermediate $k_\theta\rho_s$ increase in the ECH heated plasmas in comparison with the NBI heated plasmas. At the same time, linear gyro-kinetic simulations show a decrease in growth rates at typical ITG scale lengths for the ECH heated plasmas. Without experimental evidence of density fluctuations at $k_\theta\rho_s$ ~ 0.1-0.5 it is unclear if the turbulence in the plasma has shifted to higher $k_\theta\rho_s$ or whether the overall turbulence levels have increased. This is an important difference especially related to overall transport changes, to know whether these are caused by a change in the type of turbulence or whether particle transport increases due to an overall increase in turbulent transport at all scales.

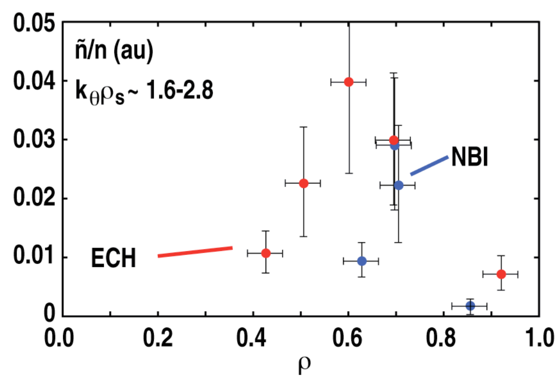

Fig. 4. Intermediate density fluctuations measured by the DBS show a strong increase for the ECH heated plasma (red) close to mid-radius in comparison with the NBI heated plasma (blue).

3. Role of ExB shear

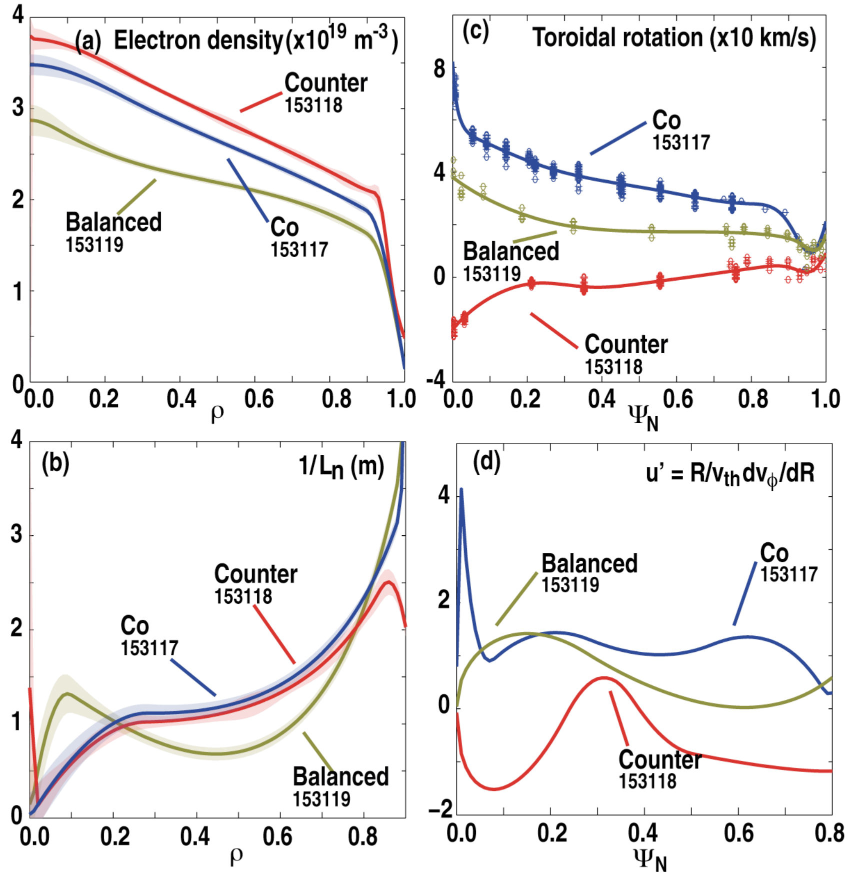

Fig. 5. (a) Density profiles change as the torque input is varied from co- to counter injection. (b) Density peaking ($1/L_{ne}$) does not increase by increasing the amount of counter injected NBI. (c) The different torque input s result in two co and one counter rotating discharge. (d) Changes in u' go from positive to negative as a result of changes in NBI injection.

In the previous section, we show that by changing from an ITG to TEM dominant plasma, the outward particle flux strongly increases. This is counter to previous experimental observations on AUG, where in H-mode plasmas, there is an improvement in particle confinement when plasmas transition from ITG to TEM [5,6]. This improvement in AUG is attributed to a change in the rotational shear, $u' = R/v_{th}\, dv_\varphi/dR$, with R the major radius, v_{th} the thermal ion velocity and v_φ the toroidal carbon rotation. In order to test this theory, we changed the torque injection in low density, dominantly ECH heated H-mode plasmas (3 MW ECH, versus 1 MW NBI). Changing the torque input and thus the toroidal rotation (see [Fig. 5(c)]) affects the overall density profile, not just the local core gradients, see [Fig. 5(a)]. We are able to change u' from a positive value to a negative value, see [Fig. 5(d)]. By changing u' from positive to negative, this will flip the off-diagonal component based on the rotation gradient from outward to inward. However, we observe no increase in density peaking as a function of u', see [Fig. 5(b)].

So the change in u' does not correlate with changes in local density gradients, nor with overall changes in particle confinement. However, a change in toroidal rotation affects turbulent transport, by changing the ExB shearing rate. In Fig. 6, we show the ExB shearing rate from ρ = 0.3-0.9 for the three discharges. The ExB shear outside ρ = 0.9, depends strongly on the chosen fits in this steep gradient region. We used a polynomial fit for these plasmas, since we are mostly interested in changes in transport in the plasma core. A tanh fit in the pedestal results in higher peak values, but the relative difference between the discharges is not affected. The ExB shearing rate can suppress turbulent transport. As a rule of thumb in a linear picture, we can assume that if the linear growth rate of the turbulent transport is smaller than the ExB shearing rate, then the ExB shear will successfully suppress turbulent transport. In the opposite case, where the linear growth rate is larger than the ExB shearing rate, the ExB shear will not successfully suppress

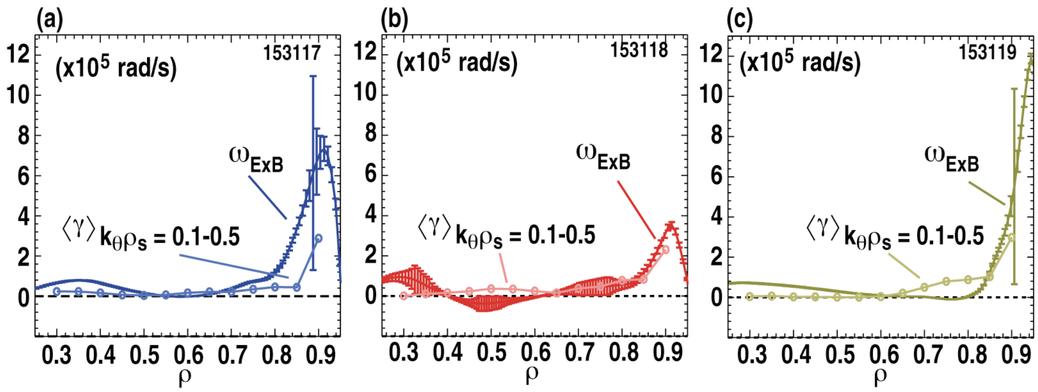

Fig. 6. The Hahm-Burrell ExB shearing rate, ω, as a function of ρ and the linear growth rate, γ, at the ITG scale for a) a co-torque injected discharge b) a counter-torque injected discharge and c) a balanced torque injected discharge. The ExB shearing rate is larger or of the same magnitude for the first two cases than the average linear growth rate, <γ>. For the balanced discharge, <γ> is larger than the ExB shearing rate close to the top of the pedestal.

transport. We find that for the discharge with the lowest overall confinement (with balanced torque injection), the linear growth rate averaged over $k_\theta\rho_s$ = 0.1-0.5, <γ>, is larger than the ExB shearing rate from ρ = 0.6-0.85 (see figure 6c). Whereas the co and counter injected discharges have linear growth rates that are of the same magnitude and/or smaller than the ExB shearing rate. This indicates that in the balanced torque injected discharge, turbulent transport is not suppressed by the ExB shear.

Experimentally using the gas puff modulation, we can extract the experimental perturbed particle transport coefficients, see [Fig. 7(a)]. We find that the case with best particle confinement, (with counter injected beams), has a very strong inward pinch component outside ρ = 0.6 (see [Fig. 7(a)]. There is not much difference in the transport coefficients for the balanced and the co-injected plasmas, even though overall particle confinement is much higher in the co-injected plasmas. One interesting observation is with relation to the intermediate scale density fluctuations, where we observe that there is nearly no difference in density fluctuations between the co and the balance injected plasmas. However, there is a strong increase in density fluctuations for the counter injected plasma from ρ = 0.7-0.92. This is at the same radial location at which we observe a strong inward pinch in the experimental perturbed transport coefficients (see [Figs. 7(a) and (b)]. A similar observation can be made in the section on turbulence regimes, where a

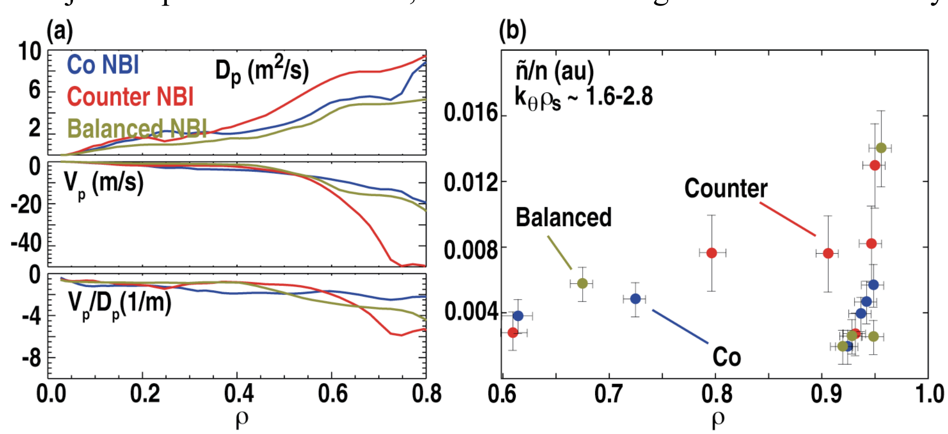

Figure 7 a) The experimentally measured perturbed transport coefficients for a co, a counter and a balanced injected discharge. b) The intermediate scale density fluctuations for a co, a counter and a balanced injected discharge.

strong increase in intermediate scale density fluctuations is observed at a similar radial location as the increase in an inward pinch ([Fig 3(b)] and Fig. 4).

4. Discussion and Conclusion

In this paper we show how changes in turbulence regimes as well as ExB shear affect particle transport. First, we show that when the plasma transitions from an ITG to a TEM turbulence regime, there is a strong increase in outward particle transport. This is in agreement with theoretical models. However, in AUG H-mode plasmas the transition from ITG to TEM is accompanied with an increase in particle confinement and an increase in the local density gradient close to mid-radius [5]. The ITG-TEM transition on AUG is marked by a strong reduction in the core rotation [6]. The peaking of the density is then explained by a change in the toroidal rotation gradient and the off-axis roto-diffusion contribution. The results in section 3, show that particle confinement does change as a result of changes in the toroidal rotation. However, there is no trend associated with u'. The changes in confinement can be simply explained by the relative changes in ExB shear in relation to the changes in linear growth rates. One could expect that in AUG, the changes in the toroidal rotation gradient will affect the ExB shearing rate and might also explain the changes in particle confinement.

One interesting observation is a strong increase in density fluctuations at the intermediate scale occurs at the same radii that we observe the creation of a strong inward pinch. We can observe this in [Fig. 3(b)] and Fig. 4. The TEM unstable plasma shows an increase in intermediate scale density fluctuations from ρ = 0.5-0.7, the same radial location at which there is an increase in the perturbed inward pinch. The same phenomenon is observed for the counter torque injected discharge, where a strong increase in intermediate scale density fluctuations from ρ = 0.7-0.9 is where we observe the existence of a strong perturbed inward pinch. It is unclear whether these are correlated observations or whether this is an accidental relationship.

One final observation is that theoretically when the plasma transitions from an ITG to a TEM regime, the group velocity of the turbulence changes sign [14]. As a result, this will affect the contribution of the intrinsic rotation to the full toroidal rotation profile. Typically in DIII-D, even without any net injected torque, the plasmas are co-rotating and are typically in the ITG turbulence regime. In order to get a discharge with zero net toroidal rotation, we need to inject a counter torque, to balance the intrinsic rotation. Most of the discharges in this paper are slightly co-injected around 0.5-1 Nm. So in the event of a change in sign of the intrinsic torque, this might not result in a 'reversal' of the toroidal rotation. It should, like in AUG, result in a strong decrease of the toroidal rotation in the plasma core [6]. We do not observe such a change in the toroidal rotation, see Fig. 8. We could question, whether the plasma actually transitions from an ITG to a TEM unstable regime. The changes in density fluctuations, as well as the changes in particle transport all point in this direction. Recent work with regards to ITG-TEM

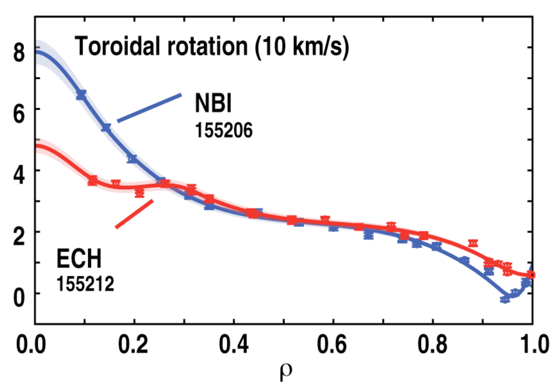

Fig. 8. Toroidal rotation for a NBI heated discharge in the linear ITG regime and for an ECH heated discharge in the TEM regime, both with 0.5 N-m co torque input.

transitions has shown that this transition might not be a necessary condition for getting a rotation reversal [15,16].

Looking forward to predictions for ITER, this paper shows that the turbulence regime as well as the ExB shear will play an important role in determining the density profile. A simple scaling of collisionality versus density peaking, or of turbulence regime versus density peaking hides other parameter changes that affect confinement (such as the ExB and the role of the toroidal rotation). Further work will focus on studying particle transport at higher densities and collisionalities. The role of the impurities and neutral fueling will play an important role based on the results from JET with respect to the ITER like Wall (ILW) [17].

Acknowledgements

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences, using the DIII-D National Fusion Facility, a DOE Office of Science user facility, under Awards DE-SC0007800, DE-FG02-08ER54984, DE-FC02-04ER54698, DE-FG02-06ER54871, DE-AC02-09CG11466, DE-FG02-89ER53296, and DE-FG02-08ER54999. DIII-D data shown in this paper can be obtained in digital format by following the links at https://fusion.gat.com/global/D3D_DMP. We would also like to thank Pieter Peers for his advice and support.

References

[1] L. Garzotti, et al. Nucl. Fusion **52** 013002 2012
[2] C. Angioni, et al. Phys. Rev. Lett. **90** 205003 2003
[3] E.J. Doyle, et al. Conf. Proc. IAEA-FEC, 2012
[4] H. Weisen, et al. Nucl. Fusion **45** 2005
[5] C. Angioni, et al. Nucl. Fusion **52** 114003 2012
[6] R.M. McDermott, et al. PPCF **53** 124013 2011
[7] S. Mordijck, et al. To be submitted Phys. Plasmas
[8] Takenaga, et al. PPCF **19** 5 1998
[9] A. Salmi, et al. Proc. EPS 2014
[10] S. Mordijck, et al. Phys. Plasmas **19** 056503 2011
[11] G.M. Staebler, et al. Phys. Plasmas **14** 055909 2007
[12] J.C. Hillesheim, et al. Rev. Sci. Instrum. **80** 083507 2009
[13] Hirsch et al. PPCF **43** 1641-1660 2001
[14] P.H. Diamond, et al. Nucl. Fusion **53** 104019 2013
[15] A.E. White, et al. Phys. Plasmas **20** 5 2013
[16] R.M. McDermott, et al. Nucl. Fusion **54** 043009 2014
[17] M.N.A. Beurskens, et al. Nucl. Fusion **54** 043001 2014