Comparison of $E \times B$ flow shear in JET and ASDEX Upgrade by Monte Carlo simulations

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Introduction: Experimentally, the anomalous transport has been found to decrease remarkably in transport barriers in context of improved confinement modes such as high (H) confinement mode. The leading paradigm for the reduction of turbulent transport in transport barriers is based on sheared radial electric field E_r. The shear in E_r can reduce transport either through stabilizing the linear modes, by reducing amplitudes or correlation lengths of turbulence, or by changing phases between the turbulent fluctuations. However, the mechanism by which the radial electric field is formed in the transition is still unclear. In Ref. [1], E_r from the radial current balance was solved with a fully kinetic five-dimensional neoclassical Monte Carlo simulation of the tokamak plasma edge in a realistic ASDEX Upgrade divertor geometry. In this paper, as a continuation of that work, the shear is simulated also for JET and the obtained shear values are compared to experimental results for the critical shear. The validity of the analysis is not limited to some special collisionality regime, thin orbit approximation is not needed, effect of E_r on ion orbits is correctly modeled also for high Mach numbers, and there is no need to make assumptions to separate different current components which consist of the same current carriers because these are consistently evaluated from the guiding-centre motion. Assuming that turbulence is electrostatic, anomalous transport can be assumed to be ambipolar which means that it does not affect the current balance. Thus, the logic of this paper is that the value of critical shear is determined by turbulence theory, but this value is reached due to neoclassical effects.

Numerical method: Time evolution of the radial electric field can be solved from $(\partial E_r/\partial t) = -\langle j_r - j_{polr}\rangle/\epsilon_\perp\epsilon_0$ where ϵ_0 is the vacuum permittivity, j_{polr} and j_r are the radial components of the polarization current and the total current, respectively, $E_r = -(d\Phi/d\rho)\langle\nabla\rho\rangle$ denotes the flux surface averaged radial electric field, Φ is the electrostatic potential, $\epsilon_\perp \approx \langle n_i m_i \nabla\rho/\epsilon_0 B^2\rangle / \langle\nabla\rho\rangle$ is the perpendicular dielectric constant, m is the mass and n the density of the particles, subscripts i and e refer to ions and electrons, respectively, and ρ is the flux surface radial coordinate. The steady-state electric field is obtained when the different current components balance each other (quasineutrality condition). Neglecting all the turbulence (except for the geodesic acoustic modes [2] included in the electrostatic model) the radial current can be written as $j_r(\rho,\theta) = j_{NCa} + j_{polr} + j_{visc}$ in which j_{NCa} is the neoclassical radial ion current arising from standard guiding-centre drifts in the presence of ion-ion collisions including also the effect of ion orbit losses. This can be solved using the guiding-centre orbit-following 5D (3D in configuration space and 2D in velocity space) Monte Carlo code ASCOT which can solve neoclassical fluxes in a realistic geometry using magnetic background from an experiment data base and is not limited to the thin orbit approximation. The polarization current, j_{polr}, is here written separately, and also the gyroviscosity current, j_{visc} (which is not a genuine guiding-center drift) is included in j_r. Current components j_{visc} and j_{polr} are generated by assigning locally to each ion the radial drift velocities [3] $v_{pol} = (1/\Omega B)\partial E_r(\rho,\theta)/\partial t$ and $v_{visc} = -(\eta/\Omega B)E_r''$ where $\eta = \eta_{Br}$ is the perpendicular Braginskii (gyro)viscosity coefficient [4] and the prime denotes the derivative with respect to the radius. The evolution equation can thus be written as

$$\frac{\partial E_r}{\partial t} = -\frac{1}{\epsilon_\perp \epsilon_0}\langle j_r - j_{polr}\rangle \approx -\frac{1}{\epsilon_\perp \epsilon_0}\langle j_{NCa} + j_{visc}\rangle, \qquad (1)$$

where $\langle j_{NCa} + j_{visc}\rangle$ is determined from the collective motion of the test particles. A steady-state is found by extending the calculation over several bounce periods and collision times. A more detailed description of the method including benchmark tests, initialization and boundary conditions, is given in [1, 5].

Results: In experiments, scalings for the critical temperature for an L–H transition have been obtained recently both at ASDEX Upgrade [6] and JET [7] as a function of toroidal magnetic field B_t, plasma density n, and plasma current I_p or safety factor q_{95}. For typical parameters of these two tokamaks, the transition temperature is essentially higher for JET than for ASDEX Upgrade. Since the analysis of the multi-machine data base gives [8] $T_{e90} \propto q_{95}^{-0.53} B_t R^{0.93}$ for the L–H transition threshold temperature, the difference between the two devices can be explained by their different major radii R.

Table 1. Reference parameters for ASDEX Upgrade (AUG) and JET.

case	a(m)	R(m)	B_t(T)	I(MA)	L_n(m)	L_T(m)	n_s(m^{-3})	T_s(eV)
AUG	0.5	1.65	-2.5	1	0.023	0.026	1.2e19	120
JET1	1	3	-2.56	2.5	0.205	0.09	1.4e19	315
JET2	1	3	-2.62	2.35	0.318	0.107	1.8e19	310
JET3	1	3	-3.47	3.55	0.06	0.06	1.0e19	300

In a series of ASCOT simulations, the plasma temperature, density, and toroidal magnetic field have been varied over a wide parameter range of ASDEX Upgrade and JET data. Reference parameters around which the B_t, n_s and T_s are varied are given in Table 1. Here, the subscript s refers to the value at the separatrix. Other parameters are not varied, i.e., profile parameters $L_n = n/n'$ and $L_T = T/T'$ are kept fixed. Here, AUG and JET1 refer to experimental data at L–H transition conditions at ASDEX Upgrade and JET, respectively. For comparison, some data points using L–mode (JET2) and H–mode (JET3) profiles' scale lengths are also included, but again, magnetic field, temperature and density are varied around the values in which experimental scaling predicts L–H transition. Using Hahm-Burrell shearing rate [9] $\omega_{E\times B} = [(RB_p)^2/B](\partial/\partial\psi)(E_r/RB_p)$ the parametric dependence $\omega_{E\times B} \propto T^{1.1} n^{0.1} B_t^{-0.85}$ $[s^{-1}]$ of the E_r shear for ASDEX Upgrade and JET is obtained from data with a ± 0.25 error margin in the exponents. The shear values are analyzed at the outboard equator where they are highest. In Ref. [1] the obtained shear values were compared to the BDT criterium [10] using the turbulence parameters from measurements in DIII-D [11] and a rough qualitative agreement was

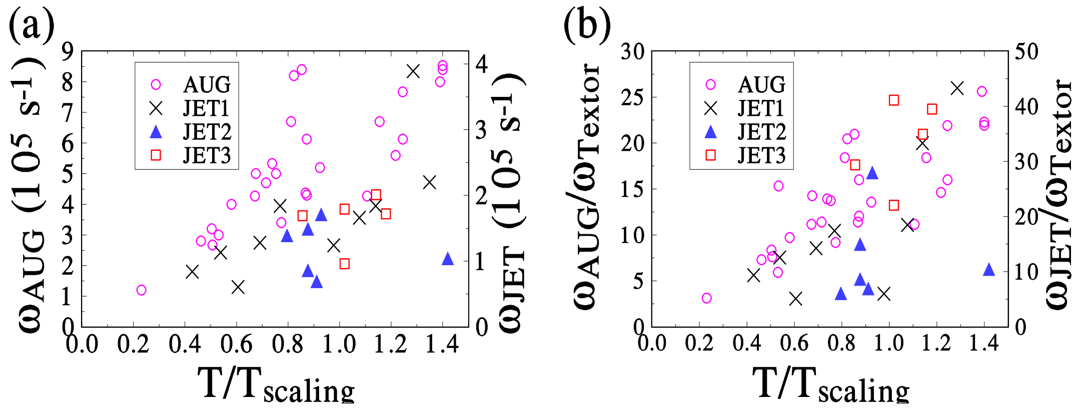

Figure 1: *a) The shearing rate $\omega_{E\times B}$, and the normalized sharing rates b) $\omega_{E\times B}/\omega_{Textor}$ from ASCOT simulation as a function T/T^{exp}_{thr}*

found between the simulated shear at threshold conditions and the critical shear. However, simulations indicated that the critical shear should be lower for JET than ASDEX Upgrade. This same result is shown in Fig. 1a, where the shear values from the simulation are plotted as a function of temperature which is normalized to the threshold temperature of each device (note the different scale of the vertical axes). Experimentally, the critical shear as a function of B_t, I_p and mass number A has been studied in TEXTOR-94 and the dependence $\omega^{crit}_{Textor} \approx 6.1 \times 10^4 B_t^{0.4} A^{-1.2} I_p^{-1.66}$ in (s^{-1}, T, amu, MA) was found [12]. Thus the dependence on I_p would justify using a lower threshold for JET plasmas than for the ASDEX Upgrade plasmas. In Fig. 1b, the simulated shear is divided by ω^{crit}_{Textor}. However, as can be seen in the figure, this does not give the right level of critical shear, i.e., it is not directly applicable to JET and ASDEX Upgrade.

In experiments, the threshold power needed for L–H transition is essentially higher when the ∇B drift is away from the X-point (unfavourable direction) than when it is towards it (favourable direction). It has been observed that keeping the heating power and all the other parameters unchanged, the edge profiles of n_e and T_e for normal and for reversed B_t are very similar [13]. Thus, in Fig. 2, the effect of reversing the direction of B_t is studied keeping the n and T profiles and all the other parameters fixed. In the ASDEX Upgrade case the edge plasma is in the collisional parameter regime and in the JET case in a collisionless regime. Here, 'normal' refers to the case were the ∇B drift is towards the X-point. The parameters are those given in Table 1 (AUG and JET1 cases). Data for the reversed field case are obtained from the data of the reference cases by simply changing the sign of B_t. In the figures it can be seen that within the limits of accuracy of the simulation, the E_r profiles do not change when B_t is reversed. Thus, the simulations with reversed magnetic field presented here can not explain the difference in L–H transition power threshold unless one assumes that the critical shear is different in the reversed field case.

Summary: $E_r \times B$ flow shear was simulated from the neoclassical current balance with the guiding-centre orbit-following Monte Carlo code ASCOT for JET and ASDEX Upgrade. Simulations indicated higher threshold shear for ASDEX Upgrade than for JET. The effect of reversing B_t on shear values was found minimal.

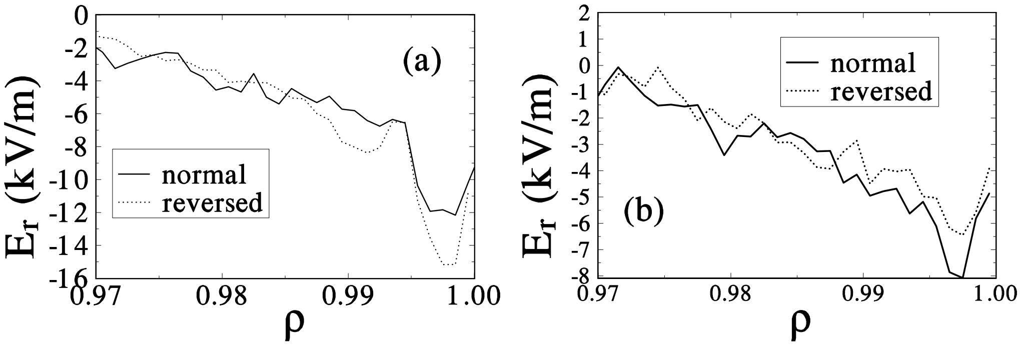

Figure 2: *Effect of reversing the direction of magnetic field at (a) ASDEX Upgrade and (b) JET is minimal if all the other parameters are kept fixed.*

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This work has been carried out under the European Fusion Development Agreement.