2nd Asia-Pacific Conference on Plasma Physics, 12-17,11.2018, Kanazawa, Japan

Critical role of sonic rotation on ion and impurity transport

Emily A. Belli[1] and Jeff Candy[1]
[1] General Atomics, San Diego, CA 92186-5608
e-mail: bellie@fusion.gat.com

The influence of sonic rotation on gyrokinetic stability and turbulent transport is studied, with important implications for heavy impurity dynamics. Sonic toroidal plasma flow, on the order of the ion sound speed, arises in tokamaks due to external torque driven by neutral beam injection and can have a profound effect on the intensity of drift-wave turbulence and corresponding levels of radial transport. Gyrokinetics typically considers the *weak rotation* limit [1], retaining only the ExB flow, Coriolis drift, and toroidal rotation shear drive. However, correct treatment of the *sonic rotation* regime [2] requires the additional consideration of centrifugal effects. Sonic toroidal rotation produces a strong centrifugal force that pushes the ions toroidally outward, causing them to redistribute non-uniformly around a flux surface. As a result of quasi-neutrality, a poloidally-varying electrostatic potential is generated to balance the density asymmetry. The equilibrium distribution retains the Maxwellian form with respect to the rotating frame,

$$f_{0a} = \frac{n_a(\psi,\theta)}{(2\pi \mathrm{v}_{ta}^2)^{3/2}} e^{-\frac{\mathrm{v}^2}{(2\mathrm{v}_{ta}^2)}} , \qquad (1)$$

where v is the rotating frame speed and $\mathrm{v}_{ta} = \sqrt{T_a/m_a}$ is the thermal speed for species a. But, while the equilibrium temperature $T_a(\psi)$ is still a flux function, the equilibrium density n_a is not, varying as

$$n_a(\psi,\theta) = N_a(\psi) e^{-\lambda_a} , \qquad (2)$$

where λ_a is the dimensionless effective potential energy, defined as

$$\lambda_a(\psi,\theta) \doteq \frac{z_a e}{T_a}\tilde{\Phi}_0 - \frac{\omega_0^2 R^2}{2\mathrm{v}_{ta}^2} . \qquad (3)$$

Here, $\omega_0(\psi)$ is the toroidal angular rotation frequency and $\tilde{\Phi}_0 = \Phi_0 - \langle\Phi_0\rangle$ is the poloidally-varying part of the equilibrium potential, which is determined by the O(1) Poisson equation,

$$\sum_a z_a e n_a(\psi,\theta) = 0 . \qquad (4)$$

In general, solution of Eq. (4) for $\tilde{\Phi}_0$ requires solving a nonlinear algebraic equation. However, for a pure plasma, there is a simple exact solution:

$$\left(\frac{1}{T_e} + \frac{z_i}{T_i}\right) e\tilde{\Phi}_0(\psi,\theta) = \frac{\omega_0^2}{2}\left(\frac{1}{\mathrm{v}_{ti}^2} - \frac{1}{\mathrm{v}_{te}^2}\right)(R^2 - \langle R^2\rangle) . \qquad (5)$$

In the kinetic equation, the centrifugal force induces a centrifugal drift, while the poloidally-varying potential produces modifications to particle trapping and the ExB drift. Because of their complexity, these new sonic terms (quadratic in the Mach number), are ignored in most neoclassical and gyrokinetic codes.

In this work, the impact of rotation on ion and impurity transport is explored with the gyrokinetic code CGYRO [3] and the drift-kinetic code NEO [4], both of which implement full sonic rotation. It is found that including only weak rotation terms, while neglecting centrifugal terms, leads to a large error, as shown in Fig. 1. While the linear ITG drive is dominantly affected by the Coriolis drift, centrifugal effects lead to significant modifications to the heavy impurity particle transport. Thus, widely-used reduced models of transport, such as TGLF, which generally do not treat the sonic regime correctly, are inadequate for studying heavy impurities. For impurities in a rotating plasma, both gyrokinetic and neoclassical transport must be considered. The turbulent transport is enhanced by the complex interaction between the Mach number and toroidal rotation shear in the drifts [5], while the neoclassical transport becomes competitive with the turbulent transport through enhanced effective toroidal curvature drifts [6]. This has significant implications for detrimental core tungsten accumulation in a reactor.

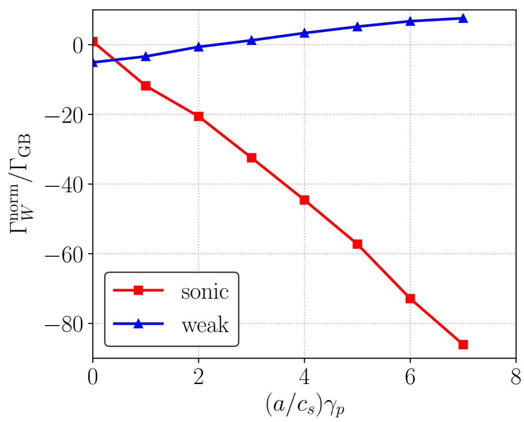

Fig. 1: Nonlinear turbulent tungsten particle flux from CGYRO vs. rotation shear, $\gamma_p = -R_0 d\omega_0/dr$. The weak rotation limit gives the wrong sign of transport. Sonic rotation gives a strong inward pinch, which could lead to impurity accumulation in the reactor core.

This work was funded by the U.S. DoE under DE-FC02-06ER54873.

References

[1] R. Waltz et al., Phys. Plasmas **14**, 122507 (2007).
[2] H. Sugama, Phys. Plasmas **5**, 2560 (1998).
[3] J. Candy et al., J. Comput. Phys. **324**, 73 (2016).
[4] E.A. Belli and J. Candy, Plasma Phys. Control. Fusion **54**, 015015 (2012).
[5] E.A. Belli and J. Candy, Phys. Plasmas, **25**, 032301 (2018).
[6] E.A. Belli, J. Candy, and C. Angioni, Plasma Phys. Control. Fusion **56**, 124002 (2014).