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Collisional Bulk Ion Transport and Poloidal Rotation Driven by Neutral Beam Injection

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Introduction

Neutral beam injection (NBI) into a tokamak plasma is known to produce a significant response and furthermore, recent experimental observations indicate that the poloidal velocity of the bulk plasma in the presence of NBI can be up to an order of magnitude larger than the standard neoclassical prediction[1]. Using a treatment which generalises previous work[3], the collisional bulk ion radial transport of particles, heat and toroidal angular momentum, as well as the bulk ion poloidal velocity, have been determined[2] for a low-collisionality plasma, allowing for the presence of a fast ion species, such as that produced by NBI. Specifically, strong toroidal plasma rotation, above the diamagnetic speed, and toroidal acceleration due to momentum deposition by the neutral beam have been accounted for, as well as the presence of toroidal rotation shear. These conditions are particularly relevant for ITB plasmas, where the thermal transport level can be comparable to the neoclassical prediction. The results are valid for arbitrary fast ion distribution functions and aspect ratio, but are restricted to plasmas with low $Z_{\text{eff}} \sim 1 - 1.2$.

The enhancement over the usual neoclassically predicted transport is seen to depend on the ratio of the beam to plasma parameters. The normalised additional contributions to the collisional heat and momentum transport due to the fast ions can be comparable. Thus, when the usual neoclassical and beam driven heat transport are comparable, the momentum flux may be significantly enhanced and comparable to the thermal transport, which is often seen to be the case in the region of an ITB[4]. Therefore, the predicted additional beam driven transport and poloidal velocity are evaluated here for a MAST[5] spherical tokamak co-NBI ITB discharge and compared to the standard neoclassical values.

Formulation

The plasma is taken to consist of two distinct components[3]: thermal bulk plasma ions (i) and fast ions (f), with their associated electrons. The formulation then follows that presented by Hinton and Wong[6]. Taking the plasma to be magnetised, the bulk ion kinetic equation is transformed to a frame rotating with the plasma, then expanded in the small parameter $\delta_i = \rho_i/L_r$, where ρ_i is the thermal ion gyroradius and L_r is the macroscopic radial scale length. To leading order, the thermal plasma on a flux surface is seen to be

Maxwellian, f_M, rotating toroidally as a rigid body due to the ExB drift, with angular frequency: $\omega(\Psi, t)$.

The source term is taken to be first-order at most. The effect of the low density fast ion species on the bulk ions is described by a Fokker-Planck collision operator. (A particle source is retained for completeness in the case of like-species injection.) Upon expanding in the small ratio of the thermal, v_{Ti}, to fast ion, v_f, velocity, retaining terms up to the order $(v_{Ti}/v_f)^2$, the gyroaveraged form may be written in the rotating frame in terms of the n-th order Legendre polynomials, P_n, in the cosines of the bulk ion pitch angle variable, ξ:

$$\bar{C}_{if} = \frac{2f_{Mi}m_i}{T_i}\left[\left(\frac{2}{3}x^2 - 1\right)P_0B_0 + \left(\frac{m_i}{m_f} - 2 + \frac{6x^2}{5}\right)xP_1B_1 - \frac{2x^2}{3}P_2B_2 - \frac{6x^3}{5}P_3B_3\right].$$

The B_n are velocity moments of the fast ion distribution function, with ξ' the fast ion pitch angle: $B_n = \gamma_{if}\int d^3w f_f \zeta_n P_n\left(\xi'\right)/w$, where w is the fast ion velocity in the rotating frame, $\gamma_{if} = z_i^2 z_f^2 e^4 \ln\Lambda / 8\pi\epsilon_0^2 m_i^2$, the factor $\zeta_n = 1$ for n even and $\zeta_n = v_{Ti}/w$ for n odd. Terms describing higher order pitch angle structure of the fast ion distribution are retained here and may be significant in determining neoclassical radial transport, due to the presence of the parallel convective term in the kinetic equation[7]. A turbulent sink, $\mathcal{D}_i$, describing the ensemble averaged contribution of fluctuations, is formally retained in the bulk ion kinetic equation[8] - the explicit value may be taken from gyrokinetic turbulence simulations. The usual neoclassical, additional beam-driven and turbulent effects are allowed to compete, depending on the ratios of beam to bulk parameters, with turbulent transport acting as a heat and momentum sink in the presence of strong NBI.

The first order gyrophase dependent part of the bulk ion distribution function is not directly affected with this form of source term. The drift kinetic equation remains linear, so the first order gyrophase independent distribution function, $\bar{f}_i$, may be written as the sum of a part driven by the radial gradients of f_{Mi}, determined in earlier work[6,9], and a part, f^b, which describes the additional structure produced by the NBI and turbulence. The radial transport is then given by modified flux-friction relations, which include the source term and time-dependent terms describing inertial effects such as the polarisation current. The transport and poloidal velocity arising from the effects of radial gradients, the NBI - that is the series of velocity moments B_n - and turbulence are therefore additive. The turbulent transport is not considered further here.

Results

High quality diagnostics covering the full plasma diameter provide the required measurements of the plasma parameters[5]. Integrated pre-processing removes interdependencies in the raw data and the TRANSP transport analysis code[10] is then used to determine the actual transport fluxes. The fast ion distribution function, as a function of radial position, poloidal angle, pitch-angle and energy, is obtained via the module NUBEAM. The transport was evaluated here for discharge #8575 at 0.19s, ($I_p = 0.77$MA, $B \sim 0.4$T, $n_i \sim 1.5\text{x}10^{19}\text{m}^{-3}$, bulk ion toroidal Mach number, $M_i \sim 0.3$) when an ITB was present at $r/a \sim 0.4$, where r/a is the square root of the normalised toroidal flux coordinate. The Z_{eff} was $\sim 1.5 - 2.0$ for r/a out to 0.6, the bulk ion collisionality was low ~ 0.05, and the parameter scale lengths in this region were longer than the ion Larmor radius, as required by the theory. The transport produced by the injected deuterium (NBI power 0.8MW, core fast ion density $\sim 2.9\text{x}10^{18}\text{m}^{-3}$) was determined, although it is noted that a second, hydrogen beam, of comparable power, was also present in this discharge.

The following results were evaluated on the outboard midplane, corresponding to the region covered by the TRANSP output. The divergence of the usual neoclassical heat and momentum fluxes were seen to be around an order of magnitude larger than the beam source term in the bulk ion energy and momentum conservation equations. Therefore the beam in this discharge corresponds to the weak source case discussed in Ref. [2] and the inertial effects may be neglected.

In Figure 1a, the resulting NBI driven collisional heat flux is shown, along with the standard neoclassical value and the experimental value determined via TRANSP, divided by a factor of 5 for comparison. The additional transport is therefore weak in this case. The peaks in the neoclassical profile are due to the form of the temperature gradient across the profile. The relative significance of the higher order velocity space structure of the fast ion distribution function may be seen in Figure 1b - in this case the B_0 driving moment dominates, which was not retained in previous work[3].

The additional beam driven, standard neoclassical and experimental radial fluxes of toroidal angular momentum are shown in Figure 2a. It is seen that the neutral beam driven angular momentum flux is comparable to the neoclassical value which accounts for an arbitrary ratio of the poloidal to toroidal magnetic field components[9]. This is a factor of 40 larger than that from the commonly used large aspect ratio expansion[6]. (For this discharge, the ratio of B_p/B_ϕ ranges from 0.15 - 0.55 over the region of interest.) Again, the relative contributions to the transport from the various B_n moments is shown in Figure 2b and the drive from the B_0 moment dominates.

Finally, in Figure 3, the NBI driven poloidal bulk ion velocity, driven predominantly by the B_1 moment in this case, is compared to the standard neoclassical value, which is driven by the temperature gradient. The two only become comparable near the core, where the temperature profile flattens.

Further work will involve applying this analysis to more recent discharges which have a lower Z_{eff} and higher neutral beam power, where the beam-driven transport may become

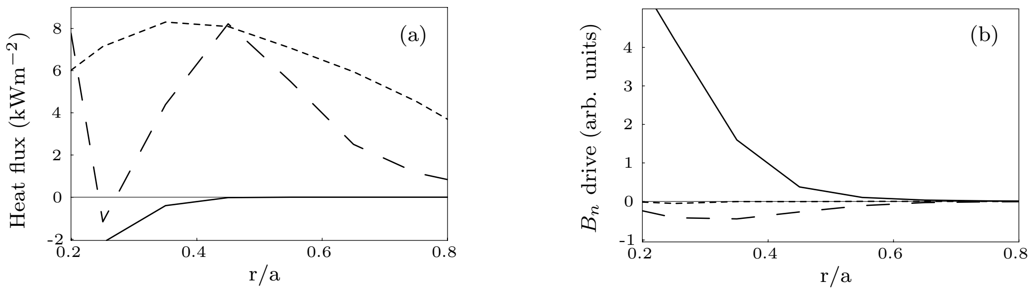

Figure 1: (a) NBI driven (solid), neoclassical (dashed) and experimental/5 (dotted) heat fluxes. (b) Relative contributions from the B_0 (solid), B_1 (dashed) and B_3 (dotted) velocity moments.

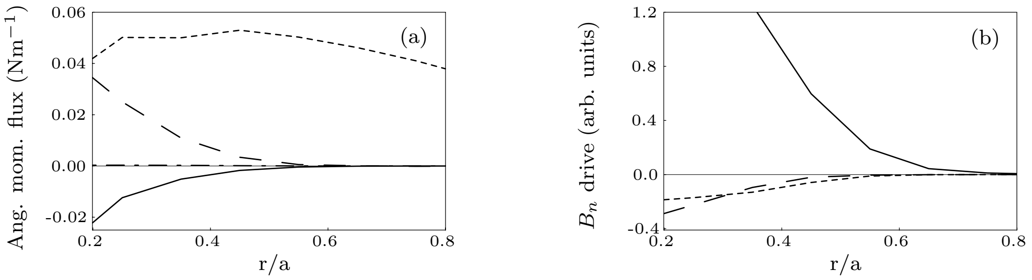

Figure 2: (a) NBI driven (solid), neoclassical (dashed), large aspect ratio (dot-dashed) and experimental (dotted) angular momentum fluxes. (b) Relative contributions from the B_0 (solid), B_1 (dashed) and B_2 (dotted) velocity moments.

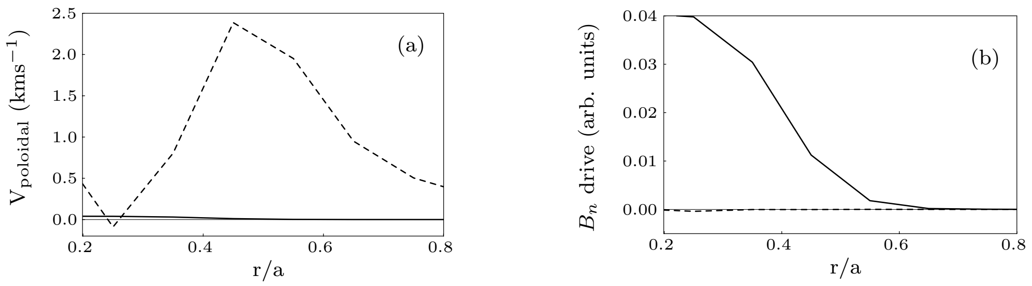

Figure 3: (a) NBI driven (solid) and neoclassical (dotted) poloidal velocity. (b) Relative contributions from the B_1 (solid) and B_3 (dotted) velocity moments.

more significant.

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