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Influence of radial electric field on stochastic diffusion in Wendelstein-type stellarators

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Confinement of fast ions, especially fusion alpha particles, is one of the most important issues for a stellarator-based reactor. In classical stellarator designs fast particles are lost on drift timescales because of ∇B drift. Various optimization schemes aim to modify magnetic configurations to improve confinement of fast ions [1]. Wendelstein-type stellarators use the quasi-isodynamic approach [2-5]: when plasma β is high enough, particle radial drift averages to zero, or in other words the contours of the longitudinal adiabatic invariant of drift motion, $J_{\|}$, become poloidally closed. Unfortunately, quasi-isodynamicity cannot be perfect, therefore some orbit losses are unavoidable. Moreover, even if perfect quasi-isodynamicity were possible, some particles can be lost. This happens because of the existence in stellarators of so-called transitioning particles, which transform between locally trapped and locally passing orbits due to drift motion. Such particles undergo stochastic (collisionless) diffusion [6, 7]. This affects the energy deposition profile of fast particles and can lead to particle losses. In principle, losses from stochastic diffusion can be reduced by a suitable modification of the magnetic configuration [8].

An important factor that affects confinement of fast ions is the radial electric field E_r, which is always present in stellarator plasmas. Neoclassical calculations show that, depending on the relation between the temperatures of electrons and ions, E_r in Wendelstein 7-X can be both positive (so-called electron root, $E_r > 0$) and negative (ion root, $E_r < 0$) [9]. In recent experiments [10-12] radial electric fields $E_r \sim$ 10~kV/m of both signs were observed, in agreement with these calculations.

The radial electric field affects orbits of locally trapped particles by modifying the contours of $J_{\|}$ [13, 14], improving confinement when $E_r < 0$ and degrading it when $E_r > 0$. The physical mechanism is that the $\mathbf{E} \times \mathbf{B}$ drift adds to or subtracts from the diamagnetic drift. When $E_r < 0$, the $\mathbf{E} \times \mathbf{B}$ drift enhances the effect of the diamagnetic drift, making the contours more poloidally closed. For $E_r > 0$ it counteracts the diamagnetic drift, and if $E_r \approx \mathrm{const} \cdot r$, cancels it completely for certain resonance values of the constant, leading to prompt particle losses [13].

The effect of E_r on stochastic diffusion has not yet been considered. It is studied in this work. A theory is developed which extends references [6-8] by taking into account the presence of the radial electric field. The obtained results can be summarized as follows.

The radial electric field influences stochastic diffusion both through change in the stochastic diffusion coefficient D_{st}, and through the modification of the shape of the separatrix between locally passing and locally trapped particles. It is shown that in Wendelstein-type stellarators, D_{st} is approximately proportional to the sum of the diamagnetic frequency of fast ions and the $\mathbf{E} \times \mathbf{B}$ precession frequency, such that ion-root radial electric field increases D_{st}, while electron-root radial electric field reduces D_{st}. This implies that negative radial electric field has opposite effects on the confinement of locally trapped and transitioning fast particles. In particular, this leads to deterioration of the confinement of transitioning fast particles in the ion-root regime.

For 50-keV NBI ions in Wendelstein 7-X, the local frequency of the $\mathbf{E} \times \mathbf{B}$ drift induced by the radial electric fields observeded in [10, 12] is comparable in magnitude to or exceeds the local diamagnetic drift frequency. For example, in discharge 20171207.006 [12] $E_r \approx -30r/a$ kV/m (a is the minor plasma radius) increases the radially averaged D_{st} in the field region by a factor of 2.5. However, this field also makes the contours of $J_{\|}$ and the shape of separatrix closer to $r = \mathrm{const}$, improving confinement, although it is insufficient to prevent losses completely through the closure of the separatrix inside the plasma volume. In the case of electron-root electric fields, their principal channel of influence on fast particle losses is not stochastic diffusion, but the opening of the $J_{\|}$ contours due to the resonance between diamagnetic and $\mathbf{E} \times \mathbf{B}$ drift frequency ($\omega_{dia} = \omega_{\mathbf{E}\times\mathbf{B}}$) [13]. For 50-keV ions in discharges 160309.024 [10] and 20171207.006 [12], this resonance is approximately fulfilled in the plasma core ($r < 0.5a$) where the radial dependence of ω_{dia} and $\omega_{\mathbf{E}\times\mathbf{B}}$ is roughly the same (linear in r). This implies that localized NBI ions will drift out of the plasma core to the periphery despite the strong suppression of stochastic diffusion coefficient (by a factor of 10).

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