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BRIEF
COMMUNICATIONS

Neoclassical Transport in Stellarators without Collisionless Ion Loss*

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Abstract—For quasi-isodynamic stellarators with poloidally closed contours of the magnetic field strength and high plasma beta neoclassical transport coefficients are computationally obtained over a large range of mean free paths. In particular, a long-mean-free-path regime is found in which quasi-neutrality obtains without radial electric field.

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Without radial electric field, ions in conventional stellarators would be lost through a loss cone [1]. Quasi-neutrality leads to the ion root [2] with inward-pointing electric field. Under special conditions [3] (e.g., $T_i \ll T_e$) an electron loss cone can lead to an electron root.

Quasi-isodynamic [4] configurations can collisionlessly confine particles, i.e., are without a loss cone. The contours of the second adiabatic invariant J are poloidally closed and, at finite β, exhibit maximum J behavior [5]; i.e., reflected ions have poloidal drifts with a sign corresponding to a radial electric field pointing inward.

The alignment of J surfaces with magnetic surfaces does not have to be perfect (and in practice is not [6]) for collisionless confinement; on the scale of collisionless electron motion, this may lead to substantial electron deviation from magnetic surfaces and, thus, transport ($1/\nu$) in the lmfp regime. This led to the conjecture that electrons may dominate over ion transport in the lmfp regime even without electric field. This expectation was verified with monoenergetic global Monte Carlo [7] neoclassical transport calculations [8] for the configuration described in [6]. In Fig. 1, a result is reproduced here, slightly augmented, for illustration of this situation. In the case considered and for vanishing radial electric field, ions are confined for about twice as long as electrons, so that quasineutrality requires an outwardly directed radial electric field, i.e., an electron root, which is a stable root at a relatively small potential height of about 2 keV. This radial electric field increases the ion transport. The mechanism is the reduction of poloidal $\mathbf{B} \times \nabla B$ drift by $\mathbf{E} \times \mathbf{B}$ drift. Complementarily, it is also obvious from the change of the contours of the second adiabatic invariant due to the electric potential; see Fig. 2.

The purpose of this simulation was qualitative insight; here, a more quantitative verification is

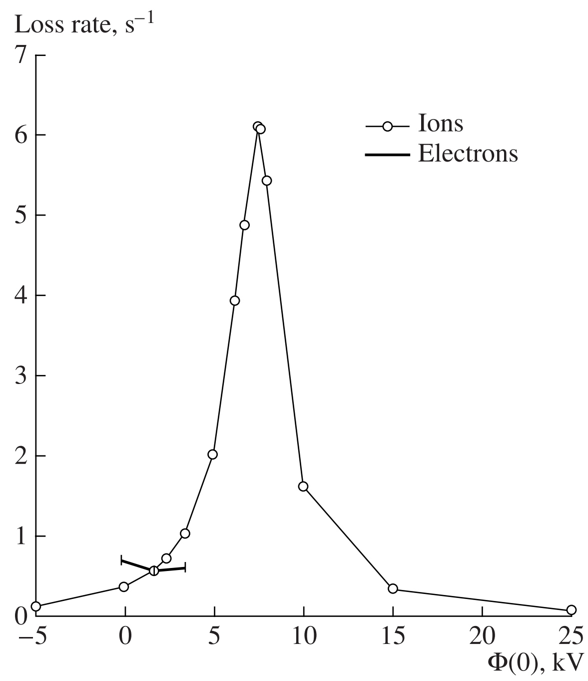

Fig. 1. Losses of monoenergetic 50-keV ions and electrons subjected to pitch-angle scattering with a normalized mean free path $L^* = 3 \times 10^3$ ($L^* = \lambda/L_c$, λ mean free path, L_c half the connection length) following the procedure of [9] versus the height of the electric potential applied in the quasi-isodynamic configuration of [6] with $\langle\beta\rangle = 0.1$, magnetic field strength $B = 5$ T, and a plasma volume of 10^3 m^3.

* The text was submitted by the authors in English.

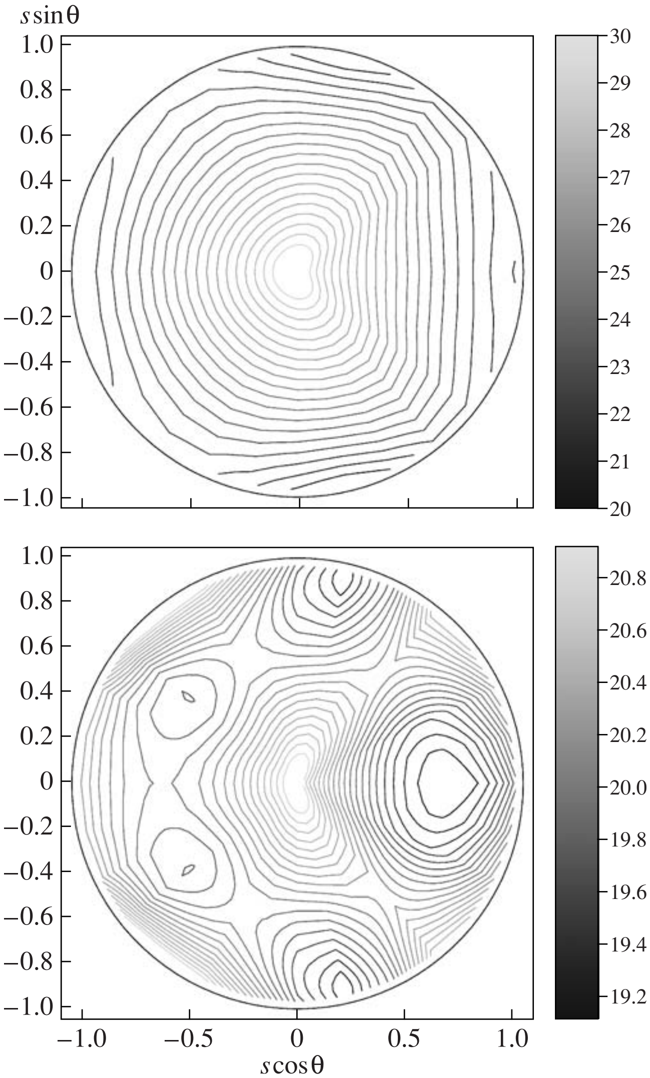

Fig. 2. Contours of the second adiabatic invariant in magnetic coordinates s (normalized toroidal flux) and θ (poloidal coordinate) of a medium-deeply reflected particle without electric potential (top) and with potential difference across the plasma radius of one-tenth of the particle's energy and the sign chosen so that the $\mathbf{E} \times \mathbf{B}$ drift counteracts the diamagnetic effect of the plasma β in the strength of B (bottom), i.e., the electric field pointing radially outward.

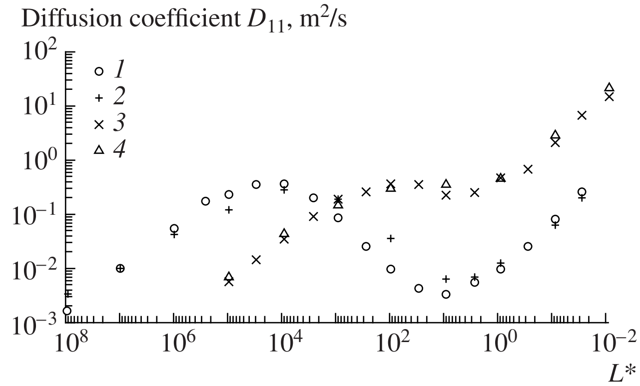

Fig. 3. Diffusion coefficients D_{11} for ions and electrons versus a normalized mean free path (the ion mean free path with respect to 90° pitch-angle scattering is used; electron results corresponding to the respective ion results are obtained at a lower mean free path (because electron–electron and electron–ion collisions need to be considered) but plotted at the ion mean free path). Symbols: ○, + for electrons; ×, △ for ions; ○, × monoenergetic results; and +, △ results with energy scattering. The configurational parameters are the same as in Fig. 1. The diffusion coefficients are obtained at half the plasma radius. For monoenergetic particles, 50 keV are again used; this value is used as the average energy of the Maxwell distributions for the ions and electrons so that $T_e = T_i \sim 33$ keV. Thus, $L^* \sim 2.4 \times 10^3$ corresponds to the density $n \sim 1.5 \times 10^{20}$ m^{-3}, which is consistent with the β value.

attempted by considering a thermal plasma locally and demonstrating that, without electric field, the diffusion coefficient D_{11} of neoclassical theory (characterizing density-gradient-driven particle flux; see, e.g., [1]) is indeed larger for the electrons than for the ions in the lmfp regime; also, the ion and electron ν regimes are obtained.

First, monoenergetic diffusion coefficients are obtained for orientation. Figure 3 shows such coefficients for ions and electrons over a very wide range of mean free paths to demonstrate the various regimes. While the ions clearly exhibit their PS and ν regimes, their $1/\nu$ regime barely exists, in keeping with the near-coincidence of the contours of the second adiabatic invariant with the magnetic surfaces [6]. On the contrary, in addition to the PS and ν regimes, the electrons exhibit a $1/\nu$ regime extending across about two orders of magnitude in the mean free path and, accordingly, diffusion coefficient, because the deviation of the contours of the second adiabatic invariant from the magnetic surfaces is large on the electron gyroradius scale. Within these simplified simulations the quasineutrality condition is satisfied at about $L^* = 2 \times 10^3$.

Second, Maxwellian ion and electron distributions with the same average energy, i.e., with a temperature two-thirds as high, are simulated; Fig. 3 shows the results. In keeping with results in [1], the ion diffusion coefficients deviate very little from the monoenergetic results. For the electrons, the $1/\nu$ regime is shifted by about a factor of 2 to a shorter mean free path so as to be qualitatively expected from the contribution of the Maxwellian-tail particles. Thus, at $L^* > 10^3$ the electron D_{11} dominates over the ion D_{11}. Again in keeping with the results in [1], one will expect D_{12} (characterizing temperature-gradient-driven particle flux; see, e.g., [1]) to be larger than D_{11} so that a further small shift of the quasi-neutrality point to a shorter mean free path is to be expected.

Thus, for the parameters used here, quasineutrality requires an electron root that should be weak in view of the above-cited result [8], but, nevertheless, helpful in avoiding impurity accumulation.

In summary, a new type of electron root for neoclassical transport in quasi-isodynamic high-β stellarators has been found.

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