Impurity Dynamics in Nonaxisymmetric Plasmas

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1. Introduction

The Stellarator Impurity Transport code (SIT)[1], describes the evolution in time and space of the impurity concentration for different charge states, corresponding convective and diffusive fluxes and radiation intensities for given plasma profiles. The calculations have been performed for several impurity species (Fe, C) for plasmas profiles typical for high-density long pulse LHD discharges [3,4]. A steady state in impurity distribution is achieved when the total flux becomes close to zero (at a fixed number of impurities) and normally on neoclassical time scales, which exceed the atomic time scales. The forces due to the radial electric field and the temperature gradient (convective terms) and density gradient (diffusive term) determine the impurity dynamics and eventually together with atomic processes the radial distribution of each ionization stage. The advanced neoclassical transport coefficients in stellarator plasmas (obtained by benchmarking of various methods [2]), has been applied to evaluate the impurity fluxes and the radial electric field.

2. Neoclassical transport coefficients

The SIT code evaluates impurity behavior in the frame of the stellarator-specific neoclassical transport, which unlike the tokamak configuration is strongly dependent on magnetic topology and the radial electric field. An analytical description of the neoclassical transport coefficient for the background plasmas (based on numerical results from the DKES code [3] and monoenergetic Monte Carlo simulations) was generalized to impurity ions of arbitrary mass and charge state and used in the code as a neoclassical transport model for impurities. An analytic description of the neoclassical transport coefficients based on numerical results from the DKES (Drift Kinetic Equation Solver) code and monoenergetic Monte-Carlo calculation (C.D. Beidler et al., EPS 1994), is here applied for impurity transport coefficients [1,2]. Two important improvements have been made. First, Pfirsch-Schlüter coefficients were corrected. In all considered here discharges [3,4] impurity ions were mainly in a collision-dominated transport regime, $\nu_I^{eff} \gg 1$, so that the correct Pfirsch-Schlüter description

was required. The reduction of the Pfirsch-Schlüter convection due to poloidal rotation caused by the radial electric field [1] has been taken into account, and its impact on the impurity dynamics due to changes in impurity diffusion coefficients, $D_{n,j}^I$ and in the electric field was investigated. Calculations show that for high density discharges the radial electric field becomes stronger, which pushes impurities rapidly towards the centre. Beyond a critical collisionality of the background plasma, $\nu_I^{eff} > \iota V / 3R_0 \Omega_E$, the poloidal rotation due to the radial electric field is sufficient to suppress the charge separation responsible for Pfirsch-Schlüter diffusion, and the losses are then reduced to the classical level. Here $\Omega_E = E_r / aB_0$, R_0 is the average minor major radii, ν_I^{eff} is the collisional frequency for impurity ions, V is the velocity of the impurity ion of mass m_I , ι is the rational transform value, $D_{n,j}^I$ is defined in [1]. So, as the collisionality increases, D_{ps}^I drops to its classical value and then becomes independent of the electric field. The drop in the D_{ps}^I coefficient results in a smaller electric field.

Another improvement has been made by including the effect of the variation of electric potential on magnetic surfaces on the radial electric field. In the case of a test impurity approximation considered here, the radial electric field is evaluated from the ambipolarity condition in the background plasma and depends on neoclassical transport coefficients for electrons and ions. In conventional stellarator neoclassical theory, the transport coefficients are determined so as to satisfy the ambipolarity constraint on the radial particle fluxes but without regard to fulfill local quasi-neutrality. This neglect is consistent with the assumption that density, and electrostatic potential, are constant on a magnetic surface. However, quasi-neutrality introduces variations of the electric potential on magnetic surfaces which can have a strong impact on impurity transport [2].

3. Calculation results.

In the Large Helical Device experiments [3,4] the influence of magnetic islands on impurity behaviour was observed by using external perturbation coils, which produce an $n/m = 1/1$ magnetic island near the plasma edge. The temperature profiles show a flattening within the island (15-20cm width), whereas the radial electric field changes the sign. A decrease of the central radiation was observed after the application of the perturbation field indicating the

retention of impurities at the edge. This can be understood, because the radial electric field changes in presence of a magnetic island and it can strongly impact the impurity behaviour.

Calculations for C and Fe ions were performed to simulate the impact of the island on the impurity accumulation. Fig. 1 shows the radial distribution of C^{+6} in different moments of time after the source term at the wall has been turned off. It is seen that after 2.5s impurity is sitting mainly within the island, where the radial electric field goes through zero and has positive sign. The different sign of the electric before and within the island causes the effective pumping of impurity ions in the island. Eventually the diffusive flux is increasing and overcomes the effect of positive electric field. This explains a slow penetration of impurities towards centre, seen in Fig.1. In case of Fe (see Fig. 2) the diffusive coefficients are less and impurities are better confined within the island. It is shown that in bulk plasma a noticeable decay in the convective inward flux due to a flattening of the plasma profiles takes place. The radial distribution of the total flux is shown in Fig. 3. One can see that the inward directed convection within the outermost part of island is adjoined to the inward diffusion. This brings about a sharp increase of impurity concentration within the island, where the electric field does through zero. This process stops once inward diffusion prevails over electric retention and as shown for C impurities they can penetrate through the electric field barrier and finally accumulate in centre. In the case of Fe ions the steady state as far as density distribution concerns was achieved within about 1.5 s. and the spatial distribution not changes any more. The impurity ions are well retained within the island. The total flux is close to zero, however the fluxes for the partial charge states are not zero within the island and slowly relaxing to zero, see Fig.4. This can indicate the importance of atomic processes within the island.

Fig. 1 C^{+6} radial distribution in different moment of time. The source at the separatrix ($\rho=1$) was turned off at $t=0.1s$. The electric field within the island changes the sign. The island width is $\Delta \approx 20cm$.

Fig. 2 Fe radial distribution at $t=1.5 s$. The source at the separatrix ($\rho=1$) was turned off at $t=0.1s$. Impurities different charge states are well screened within the island. The island width is $\Delta \approx 20cm$.

Fig. 3 Total flux of C6+ (the sum of diffusive and convective fluxes). The radial distribution at different moments of time.

Fig. 4 Diffusive and convective fluxes of C6+ are shown at different moments of time.

Calculations have also been performed for Fe and C for background plasmas profiles typical for the HDH and NC configuration in W7-AS [6] (see Fig. 5). The NC case with the peaked density profile is characterized by impurity accumulation at the centre, while in the HDH case with the flat density profile in the bulk plasma and steep at the edge, impurity is mainly radiated from the edge region [7]. A source of neutral impurity atoms was specified at the wall and can be varied in time. The radial electric field (see Fig. 5) is in both cases negative, but for HDH is rather small, particularly at the edge. A steady state impurity distribution is achieved, when the source term is switched off and the convective flux turns to zero. A comparative analysis of the diffusive and the convective fluxes shows that, in steady state impurities are localized radially, where these fluxes are compensate each other. In the HDH mode of operation the flat density profile in the bulk plasma slows down the inward impurity penetration in this region.. In the NC mode, the convective term dominates the transport and brings about a rapid accumulation of impurities in the bulk plasma. In both operational modes impurities are predominantly in the Pfirsch-Schlüter regime, $\nu_I^{eff} \gg 1$, so that the correct Pfirsch-Schlüter description was important.

The thermal diffusion coefficient is negative, for all considered profiles, thus excluding the temperature screening effect, except for the case with very low and flat density profiles and low charge states. Calculations show that the impurity convection is very sensitive to the value of the electric field and, hence to the plasma profiles. In the HDH mode, convection in the bulk region is smaller than in the NC mode. At 0.05 sec impurities are still at the edge, whereas in the NC mode impurities are already distributed in the centre. In both regimes impurity ions finally accumulate eventually at the centre and the “temperature screening” coefficient is always negative (no “screening”). However, the inward convective drift in the case of the HDH mode is smaller than in the NC mode, because of the flat density gradient and,

ultimately, due to the smaller value of the electric field. Fig. 7 shows, that in both cases Fe impurity ions are accumulating in the centre. Calculation shows that, in the frame of correct stellarator-relevant neoclassical theory, it is impossible to explain retention of impurities at the plasma edge, seen in the HDH mode of W7-AS [10, 11]. However, the typical timescales needed to reach steady state ~ 0.1 sec in the HDH plasma, and 3-5 times less in the case of NC, are of the same order of magnitude as in experiments [11].

Calculations show that the radial electric field plays a dominant role in impurity dynamics and localization. In case of low density and high temperatures (positive radial electric field) one can probably expect impurity retention at the plasma edge. Another possibility is realized in HDH mode of W7-AS.

The different impurity behavior in NC and HDH modes could be explained as a result of change in sign of the radial E-field at the edge from negative (in NC or H* mode) to positive, with pronounce screening effect. The main signature of HDH is the increase of average beta value, which causes a strong ergodization of the edge area. At some higher beta value, a stochastic area is setting up in the edge region beyond the pedestal region. Calculations done in [14] for Helias finite-beta equilibrium case confirm, that with increasing beta the width of the macroscopic islands at the edge increases, showing the trend to overlapping and ergodization. The ergodization could change a sign of the electric field in this area, making it positive due to dominant electron losses. In NC mode beta is small and the E-field is negative in entire area. With increase of average density we are approaching H* mode, which has higher beta value, than in NC mode, but not sufficient for effective ergodization. When average pressure (beta) is increasing further the edge region is ergodized stronger, and the positive E-field prevails over the diffusivity.

Let's summarize. A new Stellarator Impurity Transport Code has been developed aiming to describe impurity behavior in the frame of stellarator-relevant neoclassical transport theory. An analytical description of the neoclassical transport coefficient for background plasmas (based on numerical results from the DKES code and monoenergetic Monte Carlo simulations) have been generalized to the impurity ions of arbitrary mass and charge number. Calculations have confirmed that a temperature screening effect does not appear in nonaxisymmetric magnetic configurations. The radial electric field plays a dominant role. Only in the case of low density and high temperatures (small negative or slightly positive radial electric field) can one expect impurity retention at the plasma edge.

Keywords: Impurity dynamics, stellarator physics

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References

- [1] Yu. Igitchkanov, Yamazaki K., Polunovsky E., Beidler C. D. and Wobig. H., submitted to Journal of Plasma and Fusion Research Vol.7, 2005
- [2] C. D. Beidler et al., Talk on Stellarator workshop, 2005, Spain (private communication)
- [3] Y. Nakamura, Y Takeiri, R. Kumazawa et al. Nucl.Fusion 43 (2003) 219
- [4] Y. Nakamura, Y Takeiri, B.J. Peterson et al., 28th EPS, Funchal, Vol.25A (2001) 14
- [5] Russel A., Hulse, Nuclear Technology/Fusion v.3, (1983), 269
- [6] Berhinger K, JET Report No. JET-R(87) 08, 1987
- [7] W.I.van Rij and S.P. Hirshman, Phis. Fluids B 1 (1989) 56
- [8] C.D.Beidler et.al., EPS 1994, ECA, 18B II (1994) 568;
- [9] H. Maassberg et. al., Physics of Plasmas, v.7, 1, 2000K.
- [10] K. Shaing et al., Phys. Fluids, **26**, 3315, 1983
- [11] H. Maassberg and K. Dyabilin, EPS, 1993
- [12] K. Shaing, Phys.Fluids, 27 (7), 1984,
- [13] K. McCormick et al., Phys. Rev. Lett., **89**, 2002
- [14] E. Strunberger, Nuclear Fusion , vol.37, No.1 (1997)19

Fig.5 Background density and temperature profiles in HDH and NC (dashed) modes of W7-AS

Fig.6 The radial electric field for NC (dashed) HDH and HDH modes of W7-AS.

Fig.7 Evolution of *Fe* ions profiles in the discharge of W7-AS.