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Impurity shielding effect in a H-mode rotating plasma

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Introduction

In this paper we consider the efficiency of impurity shielding due to poloidal plasma rotation in the W7-AS stellarator. Strong fuelling results in the transition from the Normal Confinement mode of operation (NC), which is typically associated with impurity accumulation at the plasma centre, to the High Density H-Mode of operation (HDH) with high average density and improved energy confinement [1]. The HDH mode density profile is broad and flat rather than peaked, whereas the temperature profile remains the same. The HDH mode shows formation of the radial electric field and a poloidal plasma rotation (several km/s) at the plasma edge. Impurity accumulation in the centre, normally associated with ELM-free H-modes, is not observed.

It is suggested that classical transport mechanisms in toroidal geometry can explain the different impurity behaviour in the W7-AS NC and HDH discharges. Calculations show that the centrifugal force mainly affects the heavy impurities in a low or moderate charge state and in case of low plasma temperature at the edge. In this case, the rotational energy of impurity ions exceeds their thermal energy. The radial localisation of impurities results mainly from competition of thermal and centrifugal force with the pressure gradient. The latter drives impurities inside the plasma column [2,4]. The computation shows that in spite of a higher pressure gradient in the HDH discharges (#55254 chosen here has an extreme density gradient at the edge) the thermal centrifugal forces are keeping the carbon ions at the edge. In contrast, in the NC mode, temperature screening alone is unable to prevent impurity accumulation. This result seems to be in qualitative agreement with experimental observation in the W7-AS.

Physics model and equations

A multi-species plasma, with the momentum and particle balance equations for electrons, background ions and impurity ions of one charge state Z is considered. The fluid approach is justified because the carbon ions are in the collisional Pfirsch-Schlüter regime. It is assumed that all species have the same temperature and that the plasma is confined within closed toroidal magnetic surfaces, ψ. To describe plasma parameters on magnetic surfaces, the Hamada coordinate system (s,θ,ξ) is used with poloidal, $\vec{e}_p$and toroidal, $\vec{e}_t$ base vectors. Then the magnetic field is represented by $\vec{B} = \psi'(s)\vec{e}_t + \chi'(s)\vec{e}_p$, $\vec{e}_p \times \vec{B} = -\psi'(s)\nabla s$ and $\iota = \chi'(s)/\psi'(s)$. The basic equations for momentum and particle balance are:

$$\rho_k \omega_{ck}\left(\vec{v}_k \times \vec{B}/B\right) - \vec{R}_k(v) = \nabla p_k + q_k n_k \nabla\phi \qquad \vec{R}_k(v) \equiv \vec{F}_k - \nabla\cdot\pi_k - I(v_k, v_k) \tag{1}$$

$$\nabla \cdot n_k \vec{v}_k = S_k \tag{2}$$

$$\nabla \cdot \sum_k q_k n_k \vec{v}_k = 0 \tag{3}$$

Here $\vec{F}_k = \rho_k \omega_{ck} \sum_{qk} \left(\omega_{ck}\tau_{qk}\right)^{-1} \left(\mu_{qk}/m_k\right)(\vec{v}_k - \vec{v}_q)$ is the friction force between the species, $\omega_{ck} = q_k B/m_k$, $\rho_k = m_k n_k$ and $I(v_k, v_k)$ is the inertial term $\rho_k\left(\vec{v}_k \cdot \nabla\right)\vec{v}_k$. In the second equation S_k is the source term, and the third equation ensures zero total current across the surfaces and serves as an equation for the electric potential, ϕ. Summation is over all species. Further, $\vec{v}_k$ and q_k are the velocity and the charge of a particle, m_k and μ_{qk} are the mass and the reduced mass correspondingly, $p_k = n_k T$ the pressure and π_k the bulk plasma viscosity. Note that the first term in the momentum equation is the dominant term of the order ~ $(\omega_{ck}\tau_k) >> 1$ and the inertial term, which contains the centrifugal and Coriolis forces is of the order ~$\Omega_k / \omega_{ck} << 1$, where $\Omega = V_\theta / r$ is angular frequency of poloidal plasma rotation. Taking the projection of the momentum equation on $\vec{e}_p$, and averaging over the magnetic surface yields :

$$\psi'(s) q_k \Gamma_k = \left\langle \vec{e}_p \cdot R_k(\vec{v}) \right\rangle \equiv -n_k m_k \left\langle \vec{e}_p \cdot (\vec{v}_k \cdot \nabla) v_k \right\rangle + \left\langle \vec{e}_p \cdot \vec{F}_k \right\rangle - \left\langle \vec{e}_p \cdot \nabla \pi_k \right\rangle \quad (4)$$

were $\langle g \rangle \equiv \int g / |\nabla \psi| dV / \int |\nabla \psi| dV$ and dV is the volume element of the magnetic surface. Here the particle flux across a magnetic surface is defined by $\Gamma_k = \langle n_k \vec{v}_k \cdot \nabla s \rangle$.

To solve equations (1-5) the expansion technique is used [5,6]. Neglecting friction terms, the viscous term and inertia in the lowest order of $(\omega_{ck}\tau_k)^{-1}$ and Ω_k / ω_{ck}, and expanding all variables into two terms: $\vec{v}_k \to \vec{V}_k + \vec{u}_k$ etc., one can find the radial flux $\psi'(s) q_k \Gamma_k = \left\langle \vec{e}_p R_k(\vec{V}) \right\rangle$ and velocity $\vec{V}_k$ in zero approximation [6]:

$$\vec{V}_{k\perp} = \left(\vec{E} \times \vec{B}\right) / B^2 + \left(\nabla p_k \times \vec{B}\right) / q_k n_k B^2 = E_k(\psi) \vec{e}_p, \; E_k = -\phi'(\psi) + P_k'(\psi) / q_k N_k \quad (5)$$

Here the variables in capital letters denote the lowest-order quantities, E_k is the poloidal flow of the particle species *k*. The remaining zero-order variables can be found from Eqs.(1-3). Inserting $\vec{V}_{k\perp}$ into the momentum equation gives the first order velocity term:

$$\vec{u}_k = \left(\vec{R}_k \times \vec{B}\right) / q_k N_k B^2 \quad (6)$$

The radial flux (4) consists of three parts: the friction force term, the viscous force term and the inertial term. In first approximation the friction force term can be expressed as

$$\left\langle \vec{e}_p F_k(\vec{u}_k) \right\rangle \approx \rho_k \omega_{ck} \sum_q \left(\omega_{ck} \tau_{qk} B^2\right)^{-1} \left(\mu_{kq} / m_k\right) \left[\left(\vec{R}_k \times \vec{B}\right) / q_k N_k - \left(\vec{R}_q \times \vec{B}\right) / q_q N_q\right] \quad (7)$$

where only the inertial and viscous zero-order terms in R_k must be retained [6]. The zero order poloidal viscous term in collision dominated plasma is:

$$\left\langle \vec{e}_p \cdot \nabla \pi_k(\vec{v}) \right\rangle = -3 \left\langle \vec{e}_p \cdot \vec{e}_p \right\rangle \tau_k N_j T_j E_k \quad (8)$$

In the next approximation, only the zero-order terms in $R_k^0 \equiv \vec{R}_k\left(\vec{V}_k\right)$ are retained in $\vec{u}_k$.

$$\left\langle \vec{e}_p \cdot F_k(\vec{u}_k) \right\rangle \approx \rho_k \omega_{ck} \sum_q \left(\omega_{ck} \tau_{qk} B^2\right)^{-1} \left(\mu_{kq} / m_k\right) \left(\vec{e}_p \cdot \vec{e}_p\right) \left[R_k^0 / q_k N_k - R_k^0 / q_q N_q\right] \quad (9)$$

The inertial term reduces to the first-order Coriolis force (the centrifugal part drops out [5]):

$$\left\langle \vec{e}_p \cdot (\vec{v}_k \cdot \nabla) \vec{v}_k \right\rangle = -\left\langle N_k \vec{v}_k \cdot (\vec{V}_k \times \Omega_k) \right\rangle, \qquad \vec{\Omega}_k \equiv \nabla \times \vec{u}_k \quad (10)$$

Using the vorticity of $\vec{V}_k$, one gets

$$\left\langle n \vec{v}_k (\vec{V}_k \times \vec{\Omega}_k) \right\rangle = C_{11} E + K_{11} \frac{\partial E}{\partial \psi} \quad (11)$$

where $C_{11} = \left\langle \rho_k \vec{v}_k \cdot \left(\vec{e}_p \cdot \vec{\varpi}_p\right) \right\rangle$, $K_{11} = \left\langle \rho_k \nabla \psi \left(\vec{e}_p \cdot \vec{e}_p\right) \right\rangle$ and $\vec{\varpi}_p = \nabla \times \vec{e}_p$ is a vorticity of the base vector, $\rho_k = m_k N_k$. It interesting to note that the centrifugal force appears in the radial flux “indirectly” through the frictional term:

$$\vec{R}_k\left(V_k\right) \equiv \vec{F}_k(\vec{V}_k) - \nabla \cdot \pi_k(\vec{V}_k) - m_k N_k\left(\vec{V}_k \nabla\right)\vec{V}_k \qquad (12)$$

The final expression for the radial flux of impurities, Γ_I which summarise all mechanisms, can be written as:

$$\Gamma_I = \left\langle \vec{e}_p \cdot \vec{e}_p \right\rangle E_I + C_{11} E_I + K_{11} \frac{\partial E_I}{\partial \psi}, \qquad \text{where } E_I = -\phi'(\psi) - P_I'(\psi)/q_I N_I \qquad (13)$$

The equation for the radial electric field can be found from the requirement that the radial current across the magnetic surfaces equals zero:

$$\sum_k q_k \Gamma_k(\varphi) = 0 \qquad (14)$$

The radial impurity distribution can finally be found by using Γ_I and solving numerically the continuity equation $\nabla_s \; \Gamma_I = \left\langle S_{I0} \right\rangle$. Note that the equations obtained here are equally valid in both tokamak and stellarator configurations.

Results and conclusions

Equations (12-13) can be solved numerically for given plasma density and temperature profiles, taken from the NC and the HDH-phases of discharges in the W7-AS. In both cases impurity ions (carbon) are in the strong collisional regime, $\nu_I^* > 1$, which justifies a classical approach (see Fig. 1). It is easy to see that the impurity flux Γ_I is $\sim(m_i/m_e)^{1/2}$ times larger than the plasma diffusion rate. This explains the quick radial redistribution of impurities during the transition time. Several forces govern the impurity behaviour. The comparable analysis of the pressure gradient of the background ions, the thermal force and the centrifugal force shows that in the NC phase impurities are increasing at the centre due to the pressure gradient which dominates the temperature screening effect (see Figs. 3,4). The centrifugal force in this case is negligible because the poloidal plasma rotation is small (see Fig. 2,4). In the HDH mode of operation the steep density gradient at the source position brings about a strong radial electric field (see Fig.3) and the centrifugal force almost cancels the driving term of the pressure gradient. The centrifugal forces can be efficient particularly for the heavy impurities, since their rotational energy can easily exceed the thermal energy. Note that the radial distribution of particular charge state will also drop towards the centre due to the atomic processes.

Thus, the impurity shielding effect at the plasma edge of W7-AS in the HDH discharges can be explained as a result of the centrifugal force, dominating in the pedestal edge region, while the temperature screening remains almost the same. Calculations show that centrifugal force is more effective for the impurities of high charge states and when the edge plasma temperature is rather low (higher poloidal Mach number). The temperature screening is essential for impurities in a relatively low charge state and in the radial positions where the temperature gradient is relatively steep (e.g. at the edge). Note that these conclusions were obtained in the framework of an entirely classical approach.

Finally, keeping in mind that $\Gamma_I - \Gamma_{e,i} \approx 0$ and Γ_I is $\sim(m_i/m_e)^{1/2}\,\Gamma_{e,i}$ we can derive a simple scaling formula (similar to one in [2,3]), which generalise the " Boltzmann type" scaling for impurity ions at given plasma parameters and poloidal rotation:

$$n_I / n_i \propto n_i^{Z-1} \;\; T^{F(A,Z)} \;\; \exp - I(A,Z) \int_r M_\theta^2 dr / r \qquad (15)$$

Here $F(A, Z, \mu_{Ti})$ and $I(M_\theta)$ are functions of the atomic mass of the impurity, A, the charge state number, Z and the poloidal Mach number $M_\theta = V_\theta / v_{Ti}$.

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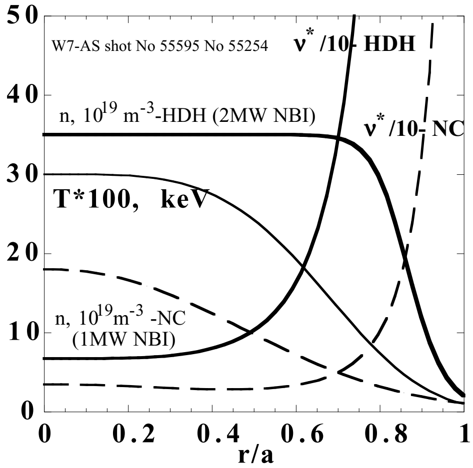

Fig.1 Experimental density and temperature profiles in the HDH- and NC-shots of discharges in W7-AS [1]; $\nu^* >> 1$ for Carbon impurities (Z=3) in both shots.

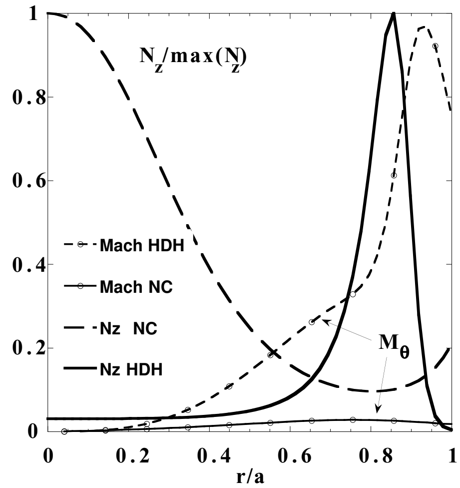

Fig. 2 Mach number and Carbon (Z=3) distribution in the NC and HDH shots; in the HDH mode the centrifugal force keeps impurities at the edge; atomic processes are not included.

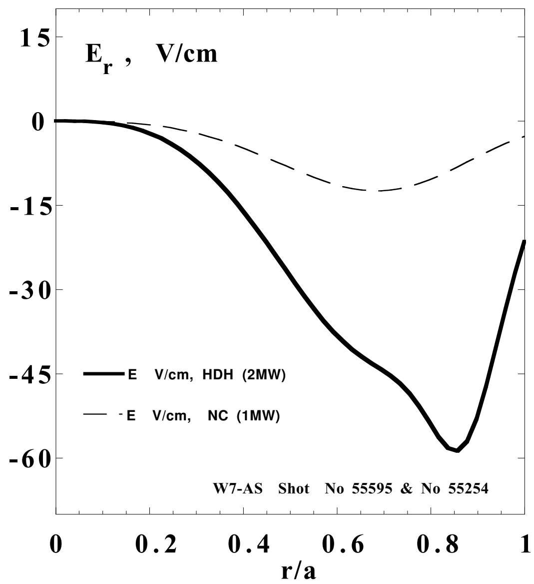

Fig.3 The radial electric field as calculated for the HDH- and NC-discharges; E_r is stronger for the HDH discharges because the pressure gradient is larger; diamagnetic contribution in E_r is dominant.

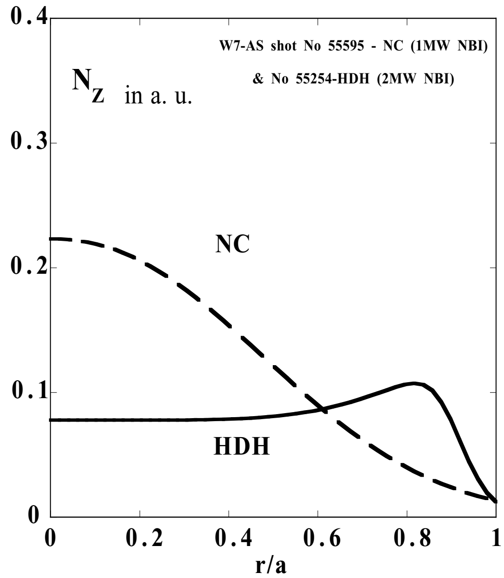

Fig. 4 Carbon radial distribution in the HDH and NC discharges in case when thermal screening is off; total number of impurity ions in both cases kept the same; atomic processes are not included.