Neoclassical Impurity Transport in Ohmically Heated Pellet Discharges

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Abstract

Pellet refuelled high density divertor discharges in ASDEX which are ohmically heated often show a sudden transition from a status of negligible or slow impurity accumulation to a fast accumulation at the plasma core. From bolometric measurements we estimate the inward drift velocity of medium z impurities and compare the results with theoretical predictions based on the neoclassical momentum equations for a two ion fluid which contain inertia and parallel viscosity.

I. Theory The theoretical calculations performed to explain the experimental observations are based on the neoclassical momentum equations for a two ion fluid (i= back ground ions, z= impurities) using a friction term derived from a shifted Maxwellian distribution only. Compared with earlier calculations /3, 4, 5/, poloidal and toroidal rotation of the background plasma is taken as two free parameters and in the impurity momentum balance parallel viscosity in the collisional and plateau regime as given in Ref. /6/ is taken into account. Parallel electric field effects are neglected corresponding to an ordering in $z \cdot m_i/m_z < 1$ (i.e., z, m_z impurity charge and mass, m_i the bulk ion mass). In addition to our previous work /7/, the complete inertial term is taken into account and it is shown to give an important contribution even in the case of zero toroidal rotation, where we obtain the following expression for the impurity transport velocity perpendicular to one magnetic surface in a geometry of circular surfaces with minor radius ρ: $\langle V_{z,\rho} \rangle = \tilde{n}_s T \varepsilon^2/(ZeB\rho)$
($T = T_e = T_i = T_z$ being the temperature, B the toroidal field $z \cdot e$ the ionic charge, $\varepsilon = \rho/R$, R the major radius). The radial flux depends only on the quantitiy $\tilde{n}_s$ which describes the up and down asymmetry in a Fourier expansion $n_z = n_z^{(0)}(1 + \varepsilon \tilde{n}_c \cos\theta + \varepsilon \tilde{n}_s \sin\theta)$.
The quantity $\tilde{n}_s$ itself depends very sensitively on the radial electric field, i.e. in the case of zero toroidal rotation considered here from the poloidal rotation of the background plasma.

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Fig. 1 shows results for neoclassical inward drifts calculated with the parameters of two typical pellet discharges in ASDEX under the assumption of zero order impurity pressure gradient $p_Z^{(0)\prime}$ to be far away from accumulation equilibrium.

$$(p_i'/n_i \gg P_Z^{(0)\prime}/z \cdot n_Z^{(0)}).$$

In opposite to the work of Rutherford /3/ which has neglected the effect of inertia and therefore has to be modified completely, the impurity transport depends beside the parameter Ω of collisionality defined as in our previous JET report /8/ also on the parameter $A^2 = V^{2\,(0)}_{z,\Theta} / \left(\frac{\varepsilon}{q} C_{z,s}\right)^2$, where $V^{(0)}_{z,\Theta}$ is the zero order impurity rotation velocity, $C_{z,s}$ the impurity sound velocity and q the safety factor.
We have always from radial momentum balance

$$V^{(0)}_{Z,\theta} = V^{(0)}_{i,\theta} - 1/eB\ (P_i'/n_i - P_Z^{(0)\prime}/zn_Z^{(0)}),$$

where $V^{(0)}_{i,\theta}$ is the bulk plasma poloidal rotation velocity. The inward drift has a maximum for $V^{(0)}_{Z,\theta}=0$, when the radial electric field E_ρ vanishes and is much smaller when the background plasma is at rest ($V^{(0)}_{i,\theta}=0$), the case which fits best to experiment. In this case theory even predicts a flow reversal for heavy impurities when $A^2 \geq 2$ an effect caused by the coefficient of parallel viscosity and leading to an interesting possibility to prove the neoclassical theory.

II. Experimental observations A transition to a phase of fast accumulation is observed a) if one or more pellets are missing during the injection of a pellet series, b) after pellet injection if no density limit disruption occurs and c) in discharges with the central radiation power density $P_{rad}(0)$ comparable to the local ohmic heating power $p_\Omega(0)$. This is observed in carbonized discharges but mainly in non-carbonized plasmas with an intrinsic higher content of iron /1/. A kind of self-triggering of accumulation occurs if the q on axis rises to values considerably above one due to high central radiation power density.
After the transition into the fast accumulating state the radiation power profiles always strongly peak in a narrow zone $r \leq r_o$ around the magnetic axis ($r_o \leq 15$cm). Little change in density and temperature profiles is observed during the transition period. No substantial variation of the radial inward drift velocity of impurities is thus expected from the neoclassical theory (see above). The postulation of a rapid decrease of the effective diffusion coefficient of impurities inside $r \leq r_o$ and no change of their inward drift velocity can explain the transition from a slow into a fast accumulation.
Sawtooth inversion radii r_{inv} similar to r_o were found in soft X-ray measurements. The onset of fast accumulation in cases a) and b) inside a zone of minor radius $r_o \approx r_{inv}$ only occurs if no pellets and no sawteeth are present. In case c) the transition occurs during repetitive pellet injection in a phase with continuous flattening of the T_e-profile, thus rising q on the plasma axis q(0). One can speculate that pellets still trigger sawteeth with q(0) just above one in case a) and b) by locally disturbing the n_e- and T_e-profile. A further rise of q(0) owing to increasing

$p_{rad}(0)/p_{\Omega}(0)$ suppresses the sawtooth activity during pellet injection. A simple analytical model is derived in order to estimate the accumulation of impurities on the plasma axis. The linearised transport equation for impurities with charge Z in cylindrical approximation is

$$-D_z(r)\cdot r\cdot\frac{\partial^2 n_z}{\partial r^2}-\left(D_z(r)+r\frac{dD_z}{dr}\right)\frac{\partial n_z}{\partial r}+V_{DZ}(r)\cdot r\frac{\partial n_z}{\partial r}+\left(V_{DZ}(r)+\frac{dV_{DZ}}{dr}.r\right)n_z=-r\frac{\partial n_z}{\partial t} \qquad (1)$$

with $n_Z(r,t)$=density, $v_Z(r)$= inward drift velocity (neoclassical) and $D_Z(r)$=effective diffusion coefficient of impurities Z.
We define $D_Z(r)$ as
$t<0$ $D_Z(r)=D_i \leftarrow (r\leq r_o)$ $D_Z(r)=D_o(r_o<r<a)$ (r_o=15 cm, a=plasma minor
$t\geq 0$ $D_Z(r)=D_a \swarrow$ radius = 40 cm)
Expansion of $v_Z(r)$ near the axis yields $v_Z=V_{D1}\cdot r$ ($v_{D1}<0$). Fast impurity accumulation starts at t=0 and no saturation of $n_Z(0,t)$ is experimentally observed until a density limit disruption occurs. For a time interval $0\leq t\leq t_A$ (t_A is estimated below) we define the velocity for outward diffusion at $r=r_o$

$$V_{DIF}=\frac{dn_z(r,0)}{dr}\cdot D_Z(r)/n_Z(r,0)_{/r=r_o} \qquad (2)$$

A time t_A is defined at which the increase of V_{DIF} at $r=r_o$ is
$\Delta V_{DIF}=V_{DIF}(r_o,t_A)-V_{DIF}(r_o,0)=0.3\cdot V_Z(r_o)$
and an experimentally detectable decrease of the time constant τ is expected. Equation 1 is simplified to

$$V_z^*(r)\cdot r\frac{dn_z}{dr}+\left(V_z^*+\frac{dV_z^*}{dr}\cdot r\right)n_z(r,t)=-r\frac{\partial n_z}{\partial t} \qquad (3)$$

$v_Z^*(r)=V_Z(r)+V_{DIF}(r)=V_{D1}(1-D_a/D_i)\cdot r=V_D^*\cdot r.$
Starting from a quasi-stationary impurity distribution $n_Z(r,0)=n_o\cdot\exp((v_{D1}/2D_i)r^2)$ $(r\leq r_o)$ at t=0, the distribution of impurities z evolves as

$$n_z(r,t)=n_o\cdot\sum_{l=0}^{\infty}\frac{(-1)^l}{l!}\left(\frac{r}{\lambda\cdot a}\right)^{2l}\cdot\exp(2|V_D^*|(l+1)t) \qquad (4)$$

$1/\lambda\cdot a=(|V_{D1}|/(2D_i))^{0.5}$
and the central density of impurities is $n_Z(0,t)=n_o\cdot e^{2|v_D^*|\cdot t}$

Figure 2 represents t_A/τ_0 ($\tau_0<\tau,\tau_0=1/(2|V_{D1}|)$ $\tau=1/2|V_D^*|$)as an upper limit of t_a/τ. Experimentally we always find $t_A/\tau>1$ (Fig. 3) and thus $t_A/\tau_0>1$. We deduce from Fig. 2 the ratio D_a/D_i to be always less than 0.3. The inward drift velocity at $r=r_0$ is derived from the experimental τ as $V_z(r_o)=r_o/2\cdot\tau$ and should always be smaller than the theoretical value.

The concentration of iron (the dominating metal in ASDEX /2/) on the plasma axis is derived from $p_{rad}(0)$ and $n_e(0)$ assuming coronal equilibrium. We always find a constant τ during accumulation and no saturation (Fig. 3).

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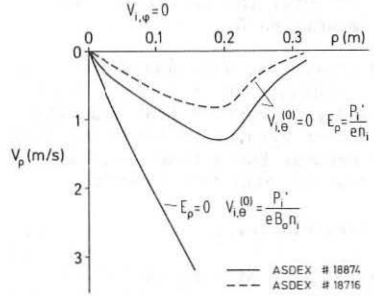

Fig.1: Neoclassical impurity inward drifts calculated for iron in a typically ASDEX pellet discharge for two different rotation velocities. Z(ρ) from corona equilibrium.

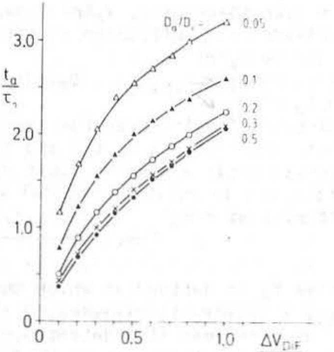

Fig.2: The increase ΔV_{DIF} of the difference outward velocity V_{DIF} related to the inward drift velocity $V_Z(r_o)$ during accumulation.

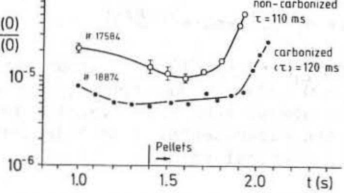

Fig.3:
#17584: non carbonized pellet discharge in D_2. The dominating metal is iron $n_Z(0) \approx n_{Fe}(0)$.
18874: carbonized pellet discharge. The T_e-profile is constant for $1.5\ s \leq t \leq 2.1\ s$ ($T_e(0) \approx 780$ eV = 30 eV). The time constant τ represents an average value for iron and titanium.

Conclusion The theoretically predicted inward drift velocity at r = 15 cm, V_z = 75 cm/s for #18716 and V_z = 110 cm/s for #18874 agree well with the bolometrically detected V_z = 43 cm/s for #18716 and V_z = 63 cm/s for #18874. The experimental values of V_z are always smaller than the theoretical V_z.