Toroidal drift and heating of impurity ions

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Toroidal drift of impurity ions has been observed in many discharges and the impurities often have apparent temperatures well above the bulk hydrogenic ion temperature $T_i$. Here the drift effect is examined in terms of local momentum transfer [1,2] from (a) a combination of the toroidal electric field and bulk electron and ion drifts induced by current flow in ohmically heated plasmas, including those with rf heating, and (b) fast toroidally circulating ions owing to neutral beam injection. Spectroscopic observations of impurity ion drift and heating in three experiments are examined: Al'fa, a diffuse pinch [3], Alcator C-Mod, a tokamak [4], and TFTR, a tokamak with strong beam heating [5]. The particles in all these plasmas tend to be out of thermodynamic equilibrium, so defining a "temperature" is problematic. Nevertheless, under standard assumptions about "temperatures" and velocity distributions, the collisional model calculations are in good agreement with experiment.

1. Model. Neglecting gradients and non-toroidal vectors, the 1-D momentum equation [1,2] for a single impurity species $x$ includes an electric field term and a collisional drag term given by a sum of contributions from near-thermal electrons and ions with drifts and, for NBI, fast suprathermal streaming ions:

$$m_x \frac{\partial u_x}{\partial t} = Z_x e E - \sum_{\beta} \mu_{x\beta} \nu_{x\beta} (u_x - u_{\beta}).$$  \hspace{1cm} (1)

$\mu_{x\beta}$ is the reduced mass and $\nu_{x\beta}$ is the momentum transfer collision rate for particles of type $x$ in field $\beta$. For ohmically heated D discharges with $n_x << n_i$, the steady-state drift velocity $u_x$ in the direction of $I_p$ for a single impurity ion $x$ ($m_x >> m_i$) is given approximately by

$$u_x \approx \frac{1.5 \cdot 10^{19} V_L / R - 3.3 \cdot 10^{16} Z_x I_p / (a^2 T_e^{3/2})}{Z_x n_e / T_i^{3/2}}.$$

The electron and hydrogenic ion drift velocities are derived from the current density and the momentum balance condition. The parameters (MKS) are: $Z_x$ impurity charge, $V_L$ loop voltage, $R$ major radius, a minor radius, $I_p$ toroidal current, $n_e$ electron density, and $T$ temperature (eV). Equation (2) preserves the electric field and electron drift terms in the numerator of Eq. (1) and the ion collision term in the denominator. In neutral beam heated plasmas Eq. (2) is supplemented by a term for the toroidally streaming ions generated by the beams. (An analogous energy equation can be derived in various ways [1,2].)

2. Al'fa. Substantial impurity drift velocities and temperatures (Doppler shifted and broadened spectrum lines) of impurity ions were observed in this diffuse pinch. A lack of
local diagnostic data makes it difficult to model its time evolution and temperatures, but
reasonable quantitative estimates of the impurity ion velocities, as well as qualitative evi-
dence of elevated impurity ion temperatures, can be obtained with the above model. Thus,
with \( R=1.6 \) m, \( a=0.5 \) m, \( Z_x=4 \), \( n_e=10^{19} \) m\(^{-3} \), \( I_p=2\cdot10^5 \) A, \( T_e=T_i=10 \) eV, and \( V_L=800 \) V \([3]\),
Eq. (2) gives \( u_x\sim3\cdot10^3 \) m/s parallel to the direction of the toroidal current \( I_p \) in Al'fa. This
case corresponds to the limit of high \( V_L \) in Eq. (2). Tokamaks, however, have low \( V_L \).

3. Alcator C-Mod. Extensive measurements of impurity ion drift have been made
on this tokamak \([4]\). The above model agrees well with observations of L-mode discharges
(\( u_x \) antiparallel to \( I_p \)) and is consistent with the reversal of \( u_x \) in H-mode and rf heated dis-
charges. Figure 1 shows the observed \([4]\) central toroidal drift (antiparallel to \( I_p \)) of \( \text{Ar}^{17} \)
ions in a deuterium Alcator C-Mod L-mode discharge (black curve). The calculated (Eq.
(1)) drift is shown as the red curve. Here the time variations of the parameters given in Ref.
4 are used and \( T_i \) is set equal to \( T_e \). The current channel is assumed to be initially con-
stricted and to broaden during plasma formation with the following peaking (as a fit pa-
rameter) for the current density: \( j(0)\pi a^2/I_p=21-22t \) (\( t=0-0.4 \) s), 20-22t (\( t=0.4-0.55 \) s), and 7.5
(\( t>0.55s \)). Rf heating and/or magnetic field changes for H-mode operation can modify the
conduction process greatly. The dashed blue curve of Fig. 1 shows the calculated impurity
drift, parallel to \( I_p \), for an (assumed) ICRF driven \( u_i=-u_e/30 \) over \( t=0.7-0.95 \) s. This large
change in \( u_i \) (and in \( u_x \)) corresponds to an increase of only about 3% in the current density.

4. TFTR. High power unidirectional NBI on TFTR yielded high impurity ion toroi-
dal drift velocities. Figure 2 shows superimposed plots \([5]\) of impurity ion velocity and
temperature with 11.6 MW of D\(^+\) (full energy \( \sim105 \) keV; flux weighted average \( \sim75 \) keV)
injected parallel to \( I_p \). The close congruence of the V and T profiles in Fig. 2 suggests a
general kinetic effect, rather than one owing to specific confinement characteristics of
TFTR. For example, plotting \( V_x(T_x) \) from Fig. 2 (also for 7.3 and 4.8 MW) gives a linear fit
with slope \( V_x(m/s)/T_x(keV)=2.7(\pm0.1)\cdot10^4 \). This is to be compared with the ratio of the final
velocity and energy of a stationary mass (\( A_2 \) amu) struck in a single 1-D elastic collision by
a much lighter particle (\( A_1<<A_2 \)) with energy \( E_F \) keV (full thermalization implies
\( kT_2=2/3E_2 \)), \( \sqrt{\nu_2/T_2}\approx3.29\cdot10^5/(A_1E_F)^{1/2} \) m/s/keV, a purely local, kinematic result. Substituting
\( E_F=75 \) keV and \( A_1=2 \) gives 2.69\( \cdot10^4 \) m/s/keV, surprisingly close to the experimental slope.
Acceleration of fast streaming ions by the toroidal electric field should be included for
evaluating impurity drift near balanced injection or comparing co- and counter-injection
results.
Figure 3 shows calculated [6] time variations in the impurity ion temperature and velocity during NBI for the conditions of Fig. 2 with a thermal $D^+$ temperature $T_i$ equal to $T_e(\text{keV})=4+4t(\text{s})$ and fast circulating ions with $E_F=75\text{ keV}$ (labelled as case 1). Also shown are the impurity ion temperatures $T_x$ for $T_i=4+8t$ (case 2) and for $T_i=T_x$ (case 3). These (and other) calculations indicate that the observed time variation in the impurity characteristics (close to curves 1 or 2) are inconsistent with equilibration of the bulk deuterium ion temperature $T_i$ to that of the impurity ions (case 3). For Fig. 2, with central $T_x\sim23\text{ keV}$, $T_x-T_i\sim7-12\text{ keV}$. In fact, the value of the "temperature" of the impurity ions (essentially equilibrated at $T_x$, and such that $T_i<T_x<E_F$) appears to be an artefact of the distinctive distribution of deuterium ions in NBI plasmas. The distributions of all three ion groups (impurities, and fast and "thermal" $D^+$) are substantially nonmaxwellian.

5. Discussion. The agreement between this model and experiments on Alcator C-Mod indicates that the impurity drift in OH tokamaks is primarily kinetic in origin (multi-component plasma) and requires no nonlocal momentum sources. These calculations assume toroidal momentum balance between the plasma electrons and ions in the central region with low $n_x$. The hierarchy of collision times for the species in these plasmas (impurity, electrons, $D^+$) confirms that the impurity drift is detached from bulk ion motion. The impurities represent a small fraction of the plasma energy and their drift is easily braked or reversed by shifts in the mechanism of current flow or changes in collision rates.

The distortion of the ion distributions has important diagnostic consequences. Detailed solutions of the kinetic equations are obviously needed. But, a model involving three detached ion groups in NBI plasmas can explain various effects, including asymmetric tangential charge exchange signals, beam induced currents, spectral lineshapes, toroidal modes and fluctuations (cf. the Strouhal number of fluid mechanics), and fusion reactivity.

Fusion reactivity in TFTR was modelled in detail early on [7]. Those calculations are readily reproduced and generalised using the above model with the corresponding energy equations and a fuelling model for the streaming ion population [6]. Both are consistent with observed neutron yield from TFTR and, in many cases, indicate overwhelming beam-beam fusion reactivity (beam-target for unidirectional injection). As far as this writer knows, no measurements of the energy distribution of fusion neutrons from TFTR (which might have settled the question of fusion mechanism) were ever made. This was done on JET, and confirmed a high thermonuclear reactivity fraction (consistent, for example, with a longer thermal ion lifetime in JET and, therefore, relatively fewer streaming ions).


Fig. 1. Impurity drift in Alcator C-Mod.

Fig. 2. Impurity ion temperature and drift velocity in TFTR. (N.B.: here $T_i$ is our $T_x$.)

Fig. 3. Calculated toroidal drift and temperature of $C^{6+}$ ions in a TFTR NBI plasma.