*33rd EPS Conference on Plasma Phys. Rome, 19 - 23 June 2006 ECA Vol.**30I**, P-4.182 (2006)*

Toroidal drift and heating of impurity ions

D.H. McNeill

Consultant, 3955 Bigelow Blvd., Pittsburgh, PA 15213, USA

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:

$$m_x \partial \mathbf{u}_x/\partial t = Z_x e\mathbf{E} - \Sigma_\beta \mu_{x\beta} \nu_{x\beta} (\mathbf{u}_x - \mathbf{u}_\beta). \qquad (1)$$

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

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

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 evidence 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 $u_x \sim 3\cdot10^3$ 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 discharges. Figure 1 shows the observed [4] central toroidal drift (antiparallel to I_p) of 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 constricted and to broaden during plasma formation with the following peaking (as a fit parameter) 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 $\mathbf{u_i}=-\mathbf{u_e}/30$ 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 toroidal drift velocities. Figure 2 shows superimposed plots [5] of impurity ion velocity and temperature with 11.6 MW of D^+ (full energy ~105 keV; flux weighted average ~75 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 $V_x(m/s)/T_x(keV)\approx2.7(\pm0.1)\cdot10^4$. 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 ($A_1 \ll A_2$) with energy E_F keV (full thermalization implies $kT_2=2/3E_2$), $v_2/T_2\approx3.29\cdot10^5/(A_1E_F)^{1/2}$ 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(keV)= 4+4t(s) and fast circulating ions with E_F=75 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~23 keV, T_x-T_i~7-12 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).

[1] A. A. Ware and J. A. Wesson, Proc. Phys. Soc. **77**, 801 (1961).

[2] V.E. Golant et al., *Fondamenti di fisica dei plasmi*, Edizioni Mir, Moscow (1983).

[3] Zh. Tekh. Fiz. **30**(12), entire issue, (1960).

[4] J. E. Rice et al., Nucl. Fus. **37**, 421 (1997). [ICRF & H-mode: PSFC/JA-05-33 (2005)].

[5] S. D. Scott et al., Phys. Rev. Lett. **64**, 531 (1990).

[6] D. H. McNeill, Bulletin APS **38**, 2040 (1993) and **39**, 1680 (1994).

[7] D. L. Jassby, Nucl. Fus. **16**, 15 (1976) and **17**, 309 (1977).

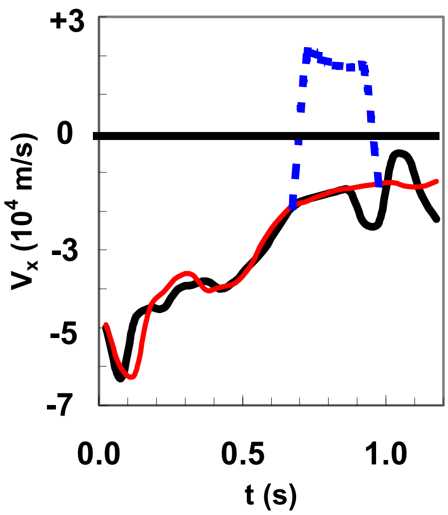

Fig. 1. Impurity drift in Alcator C-Mod.

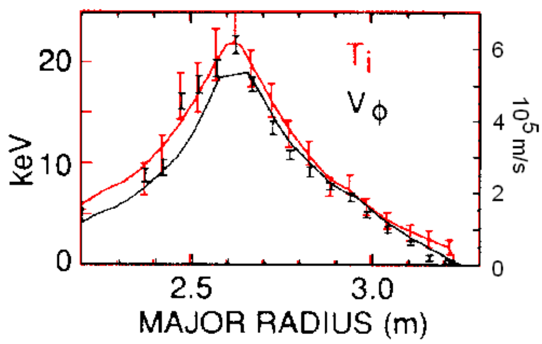

Fig. 2. Impurity ion temperature and drift velocity in TFTR. (N.B.: here T_i is our T_x.)

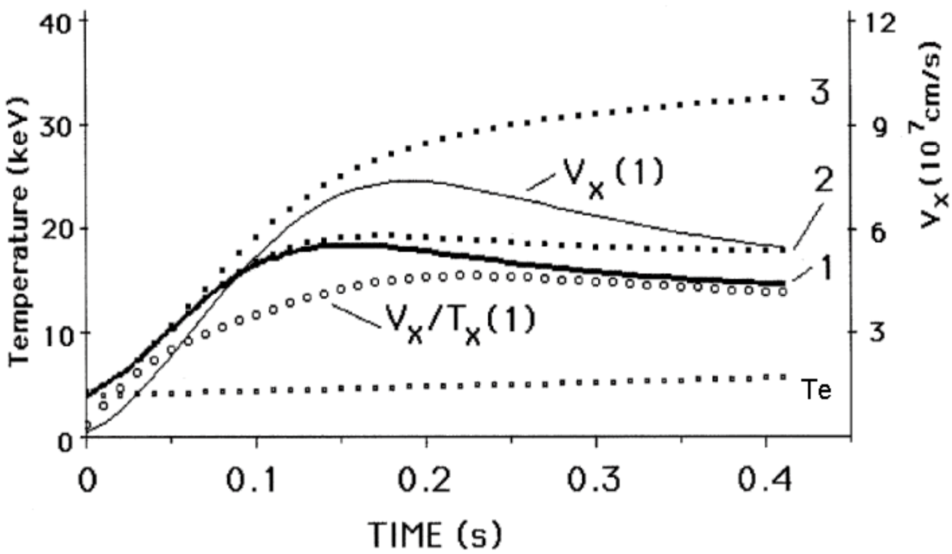

Fig. 3. Calculated toroidal drift and temperature of C^{6+} ions in a TFTR NBI plasma.