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Radial Force Balance and Radial Current Generation in the H-1 Heliac

SHATS Michael.G.*, SOLOMON Wayne.M. and TALMADGE Joseph.N.[1]
Plasma Research Laboratory, Research School of Physical Sciences and Engineering, The Australian National University, Canberra, ACT 0200, Australia
[1]Torsatron-Stellarator Laboratory, Department of Electrical and Computer Engineering, University of Wisconsin-Madison, Madison, Wisconsin 53706, USA

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Abstract

Modifications in the fluctuation-driven transport lead to improved particle confinement in the H-1 heliac. Fluctuations are either suppressed (quiescent H-mode) or the phase between the density and potential fluctuations is modified so that the fluctuation-driven particle flux reverses to become radially inward (fluctuating H-mode). In both scenarios modifications in the turbulent transport are correlated with the generation of the sheared radial electric field. We analyze the radial force balance in the two high confinement modes in H-1. A fine structure of the radial electric field observed in the fluctuating H-mode can not be explained using zero-order radial force balance. A balance deficit in this mode is observed in the radial region where fluctuations have a maximum, indicating that an internal radial current can be driven by the fluctuations. A non-ambipolarity in the fluctuation-produced transport can be responsible for the formation of the potential flow.

Keywords:

improved confinement, turbulent transport, radial electric field, radial force balance

1. Introduction

Transitions to improved confinement modes observed in the H-1 heliac at low magnetic fields (< 0.1 T) and low temperatures (T_e < 30 eV, T_i ~60 eV) [1,2] show many features of the confinement bifurcations in other toroidal experiments. It has been shown that the radial electric field plays a key role in the confinement improvement in H-1 through modifications in the fluctuation-driven transport [3,4].

Across transitions to improved confinement modes fluctuations are either suppressed in the quiescent high mode (H_q mode), or the phase between the density and potential fluctuations (fluctuation cross-phase) is modified so that the fluctuation-driven particle flux reverses to become radially inward in the fluctuating high mode (H_{fl} mode) [4,5]. It has also been found that in both scenarios modifications in the turbulent transport are correlated with the generation of the sheared radial electric field. A strong negatively sheared electric field ($E'_r < 0$) is observed in the H_q mode, while in the H_{fl} mode a positive electric field shear ($E'_r > 0$) is formed in the inner plasma region.

The radial reversal on the fluctuation-driven transport observed in H-1 has also been found in the TEXTOR-94 tokamak [6] and has recently been externally generated at the edge of the CHS heliotron/torsatron [7]. In these experiments, similarly to H-1, the radial reversal in the fluctuation-driven particle flux is correlated with the formation of the positive E_r shear

Corresponding author's e-mail: Michael.Shats@anu.edu.au

($E'_r > 0$).

In this paper we compare the radial electric field profiles in different confinement modes in the H-1 heliac and investigate the radial force balance in these plasmas. The ion flow velocities in H-1 have been reported to be significantly lower than the $\boldsymbol{E} \times \boldsymbol{B}$ drift velocities, so that the radial electric field is balanced, on average, by the ion pressure gradient term [2]. Here we analyze the detailed radial force balance in two confinement modes: quiescent high mode and fluctuating high mode. Problems in establishing detailed balance are discussed and are shown to be correlated with the presence of strong coherent fluctuations.

2. Phenomenology of Confinement Transitions in H-1

The H-1 heliac is a 3-field period helical axis stellarator [8] which has a major radius of $R = 1.0$ m and an average minor radius of $\langle a \rangle = 0.2$ m. The magnetic field structure of H-1 in the described experiments is characterized by a relatively high rotational transform ($\iota = 1.45$) and very low global magnetic shear ($\hat{s} = (\rho/\iota)(d\iota/d\rho) \approx 0.005$).

Confinement transitions are observed in the H-1 heliac at low magnetic fields (< 0.15 T), moderate heating power (< 100 kW of rf at 7 MHz) and relatively high ion temperatures (up to 80 eV) [2]. In the discharges in argon, line radiation dominates the energy confinement and limits the electron temperature to less than 20–30 eV.

Examples of spontaneous transitions from low to high modes are shown in Fig. 1.

Transitions to the "quiescent" high confinement mode (Fig. 1 a) correlate with a significant increase in the electron density, ion temperature and the radial electric field and is correlated with reduction in the fluctuation-driven particle flux by two orders of magnitude. Strong ($\tilde{n}/n \approx 0.2$) fluctuations in low confinement mode (prior to the transition) have been identified as unstable resistive pressure-gradient-driven modes [4] having low poloidal m and toroidal n mode numbers ($m = 1,2$ and $n \approx 3$) and frequencies in the range of 4 to 15 kHz in argon discharges.

An example of a spontaneous transition to the fluctuating high confinement mode is shown in Fig. 1 (b). In this discharge the improved confinement mode is characterized by about 50% increase in the average electron density, up to 50% increase in the ion temperature and more peaked n_e and T_i profiles similar to those in the quiescent high mode. The major difference between the two modes of improved confinement is that the fluctuation level does not show any significant decrease across the transition to the "fluctuating" high mode.

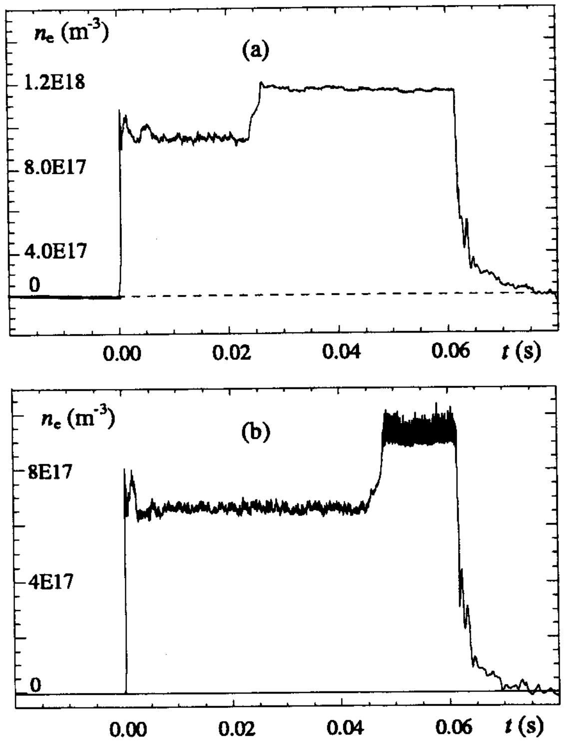

Fig. 1 Evolution of the chord-average electron density during the transitions to the "quiescent" (a) and "fluctuating" (b) high confinement modes.

3. Radial Force Balance Results

A zero-order radial force balance equation

$$E_r = (z_i e n_i)^{-1} \nabla P_i - V_{\theta i} B_\phi + V_{\phi i} B_\theta \qquad (1)$$

(where $z_i e$ is the ion charge, n_i is the ion density, P_i is the ion pressure, $V_{\theta i}$ and $V_{\phi i}$ are the poloidal and toroidal rotation velocities, respectively and B_θ and B_ϕ are the poloidal and toroidal components of the magnetic field) has been studied experimentally in the two high confinement modes.

Radial electric field was measured using two radially displaced (Δr~12 mm) triple probes ($Er = (V_{p1} - V_{p2})/\Delta r$), ion temperature was measured using retarding field ion energy analyzer [2] and the ion drift velocities in poloidal and toroidal direction were measured using Mach (or paddle) probes as discussed in [2,9]. The description of the probe techniques used is given in [9,10]. Results on the ion temperature and the ion flow velocities have also been confirmed by spectroscopic measurement of the Doppler shift and Doppler broadening [11].

Figure 2 shows radial profiles of the plasma parameters in H_q and H_{fl} confinement modes: electron density (Figs. 2 (a) and (e)), radial electric field (circles in Figs. 2 (b) and (f)), right-hand-side of the Eq. (1) (squares in Figs. 2 (b) and (f)). A root-mean-square value of the fluctuations in the ion saturation current I_s =

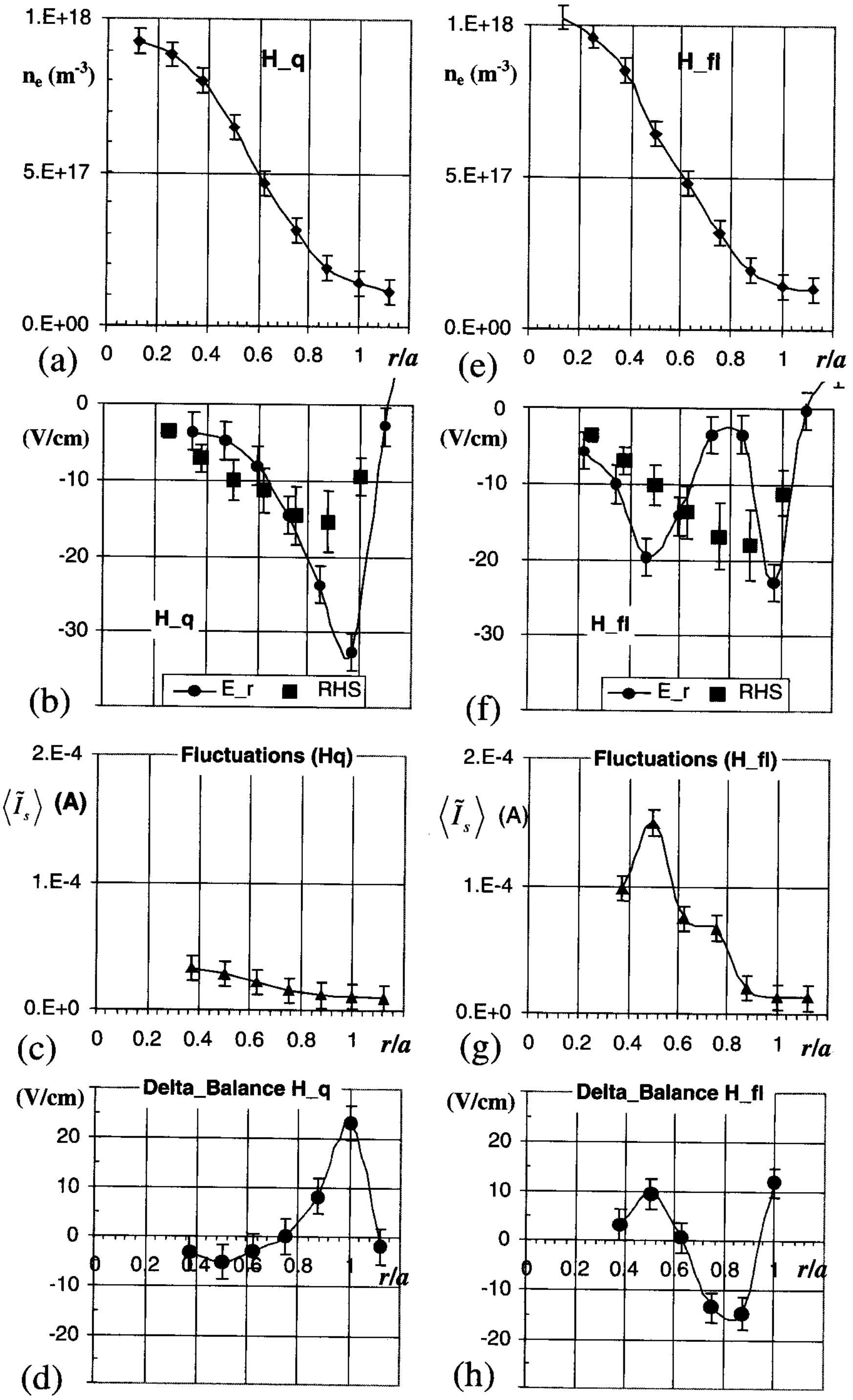

Fig. 2 Radial profiles in "quiescent" (a)–(d) and "fluctuating" (e)–(h) high confinement modes.

qAc_sn_e (where c_s is the ion acoustic velocity) is shown in Figs. 2 (c) and (g). Finally, shown in Figs. 2 (d) and (h) is the radial force balance deficit expressed as $\Delta Balance = (z_i e n_i)^{-1} \nabla P_i - V_{\theta i} B_\phi + V_{\phi i} B_\theta - E_r$. As we already mentioned, both poloidal and toroidal ion flow velocities are found to be considerably lower than the corresponding $V_{E\times B}$ drift velocities in all confinement modes in H-1, so that the radial electric field should be balanced by the ion pressure gradient term, though we include the velocity components in our analysis.

In the H_q mode this balance is approximately within error bars in the inner plasma region ($r/a < 0.8$) as shown in Fig. 2 (b). Near the last closed flux surface ($r/a = 0.8 - 1$) the balance deficit can be as high as 20 V/cm as seen in Fig. 2 (d). In the H_{fl} mode the deficit of the radial force balance extends also to the region from about $r/a = 0.4$ to $r/a = 0.8$. It has been reported [4,7] that it is this radial region of $r/a = 0.5 - 0.8$ where the fluctuation-driven particle flux is radially reversed to become inward and where the radial electric field shear becomes positive ($E'_r > 0$).

4. Discussion

The deficit in the zero-order radial force balance can be attributed to the fact that the standard ordering does not hold under conditions of our experiment. Firstly, it is the parameter ρ_i/L (ion gyroradius over radial scale length) which can not be neglected in our experiment. If L is the ion pressure scale length, $L_p = [(1/P_i)(\partial P_i/\partial r)]^{-1}$, then at $T_i = 30$ eV $\rho_i/L_p \sim 1$. The radial electric field squeezes ion orbits [3] but this effect is not strong. In the presence of the observed radial electric field this parameter can reduce to ~0.5. We also can not neglect terms of the order of $\omega_{E\times B}/\omega_{ci}$ (**$E\times B$** angular frequency over the ion cyclotron frequency) which in our conditions appear to be of the order of 0.5 to 0.8. Higher order terms should be retained in the momentum balance equation (see, for example, [12]): $E_r = \frac{1}{q_i n}\frac{\partial P_i}{\partial r} - V_{\theta i} B_\phi + V_{\phi i} B_\theta +$ higher_order_terms. Theoretical analysis of this equation when $\rho_i/L_p \sim \omega_{E\times B}/\omega_{ci} \sim 1$ is somewhat difficult. This difficulty is amplified by the fact that ions are not really localized on flux surfaces, but rather loosely confined due to the combined effect of the magnetic and the radial electric field [3]. Under these conditions it is hard to expect ions to be responsible for the formation of the fine structure in the radial electric field (with $L_{Er} = [(1/E_r)(\partial E_r/\partial r)]^{-1} \sim \rho_i$) observed in H_{fl} mode. Instead, we try to draw some conclusions on the physical processes involved in the balance deficit by comparing the balance deficit profiles in H_q and H_{fl} modes. The largest radial force balance deficit in H_q mode is observed at the edge (Fig. 2 (d)), about one ion gyroradius deep inside the last closed flux surface. This coincides with the region of the direct orbit loss and is amplified by the charge-exchange with neutral particles. In H_{fl} mode (Fig. 2 (d)), in addition to the edge, the balance deficit is strong in the radial region of $r/a = 0.5 - 0.8$. It is in this region where fluctuations remain strong and the fluctuation-produced particle flux is modified in H_{fl} mode to become radially inward [4], while in H_q mode fluctuations are effectively suppressed.

We may suggest that if fluctuations produce non-ambipolar particle flux, they can locally modify the radial electric field, generating "bumpiness" in the E_r profile. If fluctuations drive predominately electron transport (it is the electron component of the turbulent fluxes that is measured using probes: $\Gamma_{fl}^{el} = \langle \tilde{n}\tilde{V}_{re}\rangle = \langle \tilde{n}\tilde{E}_p\rangle / B_{tor}$) then this anomalous non-ambipolar particle flux could contribute to the E_r modification in the electron radial force balance and through it affects the ion radial force balance reported here. In steady state the electron and ion fluxes balance each other, so that the net radial current is zero, $\Gamma^{el} = \Gamma^{ion}$.

Indeed, it has been shown in [5] that the fluctuation-driven (electron) radial flux can be as high as $\Gamma_{fl}^{el} = 3 \times 10^{20}$ m^{-2}s^{-1}. Radial resistivity at $r/a = 0.6$ estimated as $\eta_r = B^2/[c^2 m_i n v_{in}(1 + 2/\iota^2)]$ [13] is about $\eta_r = 20$ Ohm·m. If we assume that the fluctuation-driven flux is totally non-ambipolar ($\Gamma_{fl}^{ion} = 0$) then the contribution of the fluctuation-driven (electron) current to the electron radial force balance will be $\Delta E_r = e\Gamma_{fl}^{el}\,\eta_r \approx 10$ V/cm, which is close to the observed balance deficit in H_{fl} mode at mid-radius (Fig. 2 (h)).

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