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Role of trapped and circulating particles in inducing current drive and radial electric field by Alfvén waves in tokamaks

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Abstract. Absorption by trapped particles is supposed to seriously hinder current drive by Alfvén waves. However, it is shown in this paper that the same effect is rather beneficial for the emergence of the radial electric field induced by these waves, which is important for creating and maintaining transport barriers in tokamaks.

1. Introduction

The main difficulty with using Alfvén waves (AWs) for current drive is supposed to be caused by their absorption by trapped particles (Kolesnichenko et al. 1990). Different physical mechanisms that may improve this situation are described by Karney and Fish (1979) and Elfimov et al. (1992). Recently, new ideas for the application of AWs in tokamaks, besides heating and current drive, have been investigated with great interest. They are all related to the electric field created by these waves at the mode resonant surface, and the associated sheared plasma rotation (Craddock and Diamond 1991; Tsypin et al. 1999), with the purpose of maintaining internal transport barriers in tokamaks (Biglari et al. 1990; Burrell 1997; Tsypin et al. 1998, 1999). In particular, a new research program has been initiated in the TCABR tokamak (Tokamak Chauffage Alfvén Brazilian) to investigate this mechanism (Galvão et al. 1999). Since the phase velocity of AWs is smaller than the thermal velocity of the electrons, they interact strongly with trapped particles. This effect, which is certainly a hindrance for current drive, has not yet been properly analyzed with regard to the creation of transport barriers. In this letter we show that, in reality, interaction with trapped particles can substantially increase the sheared poloidal and toroidal rotation induced by kinetic AWs.

2. Starting equations

It was previously shown that radiofrequency (RF) forces, affecting electrons, $\boldsymbol{F}_e^h$, and ions, $\boldsymbol{F}_i^h$, respectively, in closed magnetic traps, can be presented in the following form (Tsypin et al. 1999) (here we are interested only in poloidal ($s = \theta$) and toroidal ($s = \zeta$) components of RF forces):

$$\langle F^h_{\alpha s}\rangle = \frac{i}{4\omega\langle\sqrt{g}\rangle}\left(\frac{\partial}{\partial r}\langle\sqrt{g}E^{ef}_{\alpha s}j^{*r}_\alpha\rangle - \left\langle\sqrt{g}j^{*k}_\alpha\frac{\partial}{\partial s}E^{ef}_{\alpha k}\right\rangle\right.$$
$$\left. + \frac{2\pi i\omega}{\omega^2_{p\alpha}}\left\langle\sqrt{g}\frac{\partial}{\partial s}|\boldsymbol{j}_\alpha|^2\right\rangle - \text{c.c.}\right), \tag{2.1}$$

where

$$E^{ef}_{\alpha k} = E_k + \frac{4\pi i\omega j_{\alpha k}}{\omega^2_{p\alpha}}, \qquad \omega^2_{p\alpha} = \frac{4\pi n_\alpha e^2_\alpha}{M_e},$$

$$\langle\ldots\rangle = \frac{1}{4\pi^2}\int_0^{2\pi}\int_0^{2\pi}(\ldots)\,d\theta\,d\zeta,$$

$\alpha = i$ and e refers to ions and electrons, respectively, r is the arbitrary radial coordinate, g is the coordinate metric, $\boldsymbol{E}$ and $\boldsymbol{j}$ are the RF electric field and the RF current, respectively, ω is the wave frequency, n_α is the particle density, and M_α is the particle mass. Here, we intend only to estimate the radial electric field and current drive induced by AWs. Thus, we average the forces in (2.1) over the narrow layer δr where kinetic AWs exist:

$$\langle F^h_{\alpha s}\rangle \approx \frac{i}{4\omega}\left(-\left\langle j^{*k}_\alpha\frac{\partial}{\partial s}E_k\right\rangle - \text{c.c.}\right). \tag{2.2}$$

We also use the quasicylindrical approximation, taking into account toroidal effects only in terms connected with electron Landau damping. As a result, (2.2) for the 'physical' components of the bounce-averaged RF force $F^h_{\alpha s}$ reduces to

$$F^{h\sigma}_{e\theta} \approx \frac{m}{\omega r}P^\sigma_w, \qquad F^{h\sigma}_{e\zeta} \approx \frac{n}{\omega R}P^\sigma_w, \qquad \langle F^{h\sigma}_{isp}\rangle \approx 0, \qquad P^\sigma_w \approx \frac{\omega}{8\pi}\,\text{Im}\,\varepsilon^\sigma_\parallel|E_\parallel|^2, \tag{2.3}$$

where m and n are poloidal and toroidal wavenumbers, respectively, P^σ_w is the absorbed power, $\sigma = t$ and c indicates trapped and circulating particles, respectively, $E_\parallel$ is the parallel component of the RF electric field, and $\varepsilon^\sigma_\parallel$ is the parallel component of the permittivity tensor; here and below, r and R are the torus minor and major radii, respectively. It has been shown that in tokamaks, AWs are absorbed mainly by trapped particles (Tsypin et al. 1997). The simplified expression for the permittivity tensor parallel component $\varepsilon^\sigma_\parallel$ is

$$\text{Im}\,\epsilon^c_\parallel = \frac{2\sqrt{\pi}\omega^2_{pe}qR}{\omega(m-nq)v_{Te}}F_c(\varepsilon), \qquad \text{Im}\,\epsilon^t_\parallel = \frac{2\sqrt{\pi}\omega^2_{pe}qR}{\omega(m-nq)v_{Te}}F_t(\varepsilon) \tag{2.4}$$

where q is the safety factor, and $\varepsilon = r/R$ is the inverse aspect ratio (see e.g. Tsypin et al. 1997). The functions $F_c(\varepsilon)$ and $F_t(\varepsilon)$ characterize absorption of AWs by circulating and trapped particles, respectively. If $\varepsilon = 0$, we have the well-known expression for the plasma-cylinder limit of (2.4):

$$\text{Im}\,\epsilon_\parallel = \frac{2\sqrt{\pi}\omega^2_{pe}}{k^2_\parallel v^2_{Te}}\frac{\omega}{k_\parallel v_{Te}}\exp\left(-\frac{\omega^2}{k^2_\parallel v^2_{Te}}\right), \qquad k_\parallel = \frac{m-nq}{qR}. \tag{2.5}$$

Estimates show that for conventional tokamaks with $\omega < \sqrt{\varepsilon}k_\parallel v_{Te}$, the condition $\text{Im}\,\epsilon^c_\parallel < \text{Im}\,\epsilon^t_\parallel$ is usually fulfilled, and, consequently, $F^{hc}_{e\theta p} < F^{ht}_{e\theta p}$ and $F^{hc}_{e\zeta p} < F^{ht}_{e\zeta p}$, i.e. the kinetic AWs are mainly absorbed by trapped particles.

Considering this result, we can understand qualitatively the effect of AWs on establishing the radial electric field. Because they are absorbed mainly by trapped particles, the forces associated with the waves do not change the basic neoclassical regime where ambipolar radial diffusion is mainly due to trapped particles. Therefore, the increase in momentum of the trapped particles, due to RF forces, enhances their radial drift and the ambipolar electric field associated with it. In this paper, we calculate the resulting electric field explicitly.

3. MHD equations for trapped and circulating particles

To describe the plasma dynamics in the presence of AWs in a tokamak plasma, we use the four-fluid hydrodynamic model, including trapped and circulating electrons and ions and neglecting diamagnetic effects, in a model tokamak equilibrium with circular magnetic surfaces (see Kolesnichenko et al. 1990 and references therein):

$$e_e n_t E_r - \frac{\partial p_t}{\partial r} - \frac{e_e n_t B_{\theta p}}{c} U^t_{\zeta e} + R^t_{er} \approx 0, \tag{3.1}$$

$$e_i n_t E_r - \frac{\partial p_t}{\partial r} - \frac{e_i n_t B_{\theta p}}{c} U^t_{\zeta i} + R^t_{ir} \approx 0, \tag{3.2}$$

$$e_i n_c E_r - \frac{\partial p_c}{\partial r} + \frac{e_i n_c}{c}(U^c_{\theta i} B_{\varsigma p} - U^c_{\varsigma i} B_{\theta p}) + R^c_{ir} \approx 0, \tag{3.3}$$

$$e_e n_c E_r - \frac{\partial p_c}{\partial r} + \frac{e_e n_c}{c}(U^c_{\theta e} B_{\varsigma p} - U^c_{\varsigma e} B_{\theta p}) + R^c_{er} \approx 0, \tag{3.4}$$

$$-\frac{\partial p_\alpha}{\partial \theta} - e_\alpha n_\alpha \frac{\partial \phi}{\partial \theta} - (\boldsymbol{\nabla} \cdot \boldsymbol{\pi}_\alpha)_\theta - \frac{e_\alpha n_\alpha}{c}(\mathbf{V}_\alpha \times \mathbf{B})_\theta + r F^h_{\alpha\theta} + r R_{\alpha\theta} \approx 0, \tag{3.5}$$

$$-(\boldsymbol{\nabla} \cdot \boldsymbol{\pi}_\alpha)_\zeta + \frac{e_\alpha n_\alpha}{c}(\mathbf{V}_\alpha \times \mathbf{B})_\zeta + R F^h_{\alpha\zeta} + R R_{\alpha\zeta} \approx 0. \tag{3.6}$$

Here, $\boldsymbol{R}$ represents the Coulomb friction between particles of different kinds:

$$R^t_{\alpha r} \approx -R^c_{\alpha r} \approx -M_\alpha n_t(\nu_{\alpha e} + \nu_{\alpha i}) U^t_r, \tag{3.7}$$

$$R^t_{\alpha\theta} \approx M_\alpha n_t(\nu_{\alpha\alpha} U^c_{\alpha\theta} + \nu_{\alpha\beta} U^c_{\beta\theta}), \tag{3.8}$$

$$R^c_{\alpha\theta} \approx -M_\alpha n_t(\nu_{\alpha\alpha} U^c_{\alpha\theta} + \nu_{\alpha\beta} U^c_{\beta\theta}) - M_\alpha n_c \nu_{\alpha\beta}(U^c_{\alpha\theta} - U^c_{\beta\theta}), \tag{3.9}$$

$$R^t_{\alpha\zeta} \approx -M_\alpha n_t[\nu_{\alpha\alpha}(U^t_{\alpha\zeta} - U^c_{\alpha\zeta}) + \nu_{\alpha\beta}(U^t_{\alpha\zeta} - U^c_{\beta\zeta})], \tag{3.10}$$

$$R^c_{\alpha\zeta} \approx M_\alpha n_t[\nu_{\alpha\alpha}(U^t_{\alpha\zeta} - U^c_{\alpha\zeta}) + \nu_{\alpha\beta}(U^t_{\alpha\zeta} - U^c_{\beta\zeta})] - M_\alpha n_c \nu_{\alpha\beta}(U^c_{\alpha\zeta} - U^c_{\beta\zeta}), \tag{3.11}$$

In comparison with the system of equations considered by Kolesnichenko et al. (1990), we use the θ and ζ components of more detailed transport equations. Here U^t_r is the 'physical' radial component of the trapped-electron and -ion velocity, and $U^c_{\beta\theta}$, $U^c_{\beta\zeta}$, $U^t_{\beta\theta}$, $U^t_{\beta\zeta}$ are the 'physical' poloidal and toroidal components of the velocities of circulating and trapped particles of type β, respectively. The collision frequencies $\nu_{\alpha\beta}$ are taken in the form given by Braginskii (1965). In obtaining (3.1)–(3.11), we have assumed that the usual neoclassical inequality $U^t_r > U^c_r$ holds, where U^c_r is the 'physical' radial component of the velocity of both circulating electrons and ions.

We note that usually the electric field is determined from (3.3) (see e.g. Burrell 1997). However, in the presence of AWs, the radial electric field was calculated by

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Kolesnichenko et al. (1990) from (3.1) and (3.2), and not from (3.3). In this paper, we reconcile the two approaches and explain when each of them can be used.

4. Dynamics of trapped and circulating particles

We solve the system of equations (3.1)–(3.11) by first following the 'classical' scheme of determining the radial electric field from (3.3), as was done by Burrell (1997). The velocities $U^c_{i\theta}$ and $U^c_{i\varsigma}$ in (3.3) can be found from (3.5) and (3.6), respectively, summed over circulating and trapped ions and electrons, and using the current continuity equation averaged over the magnetic surface, $\int \boldsymbol{\nabla}\cdot\mathbf{j}\,d\mathbf{r} \approx 0$. As a result, we have from (3.5) and (3.6), respectively,

$$U^c_{i\theta} \approx 1.17\,U_{Ti} + \frac{F^h_\theta}{\mu_{i\theta}}, \qquad U^c_{i\zeta} \approx \frac{F^h_\zeta}{\mu_{i\zeta}}, \tag{4.1}$$

(Rosenbluth et al. 1972; Tsypin et al. 1999), where

$$U_{Ti} = \frac{1}{\omega_{ci} M_i}\frac{\partial T}{\partial r},$$

$\omega_{ci} = e_i B/cM_i$ is the ion cyclotron frequency, $B = (B^2_{\zeta p} + B^2_{\theta p})^{1/2}$ is the magnetic field, $\mu_{i\theta} \approx 1.1 M_i n_c q^2 \nu_{ii}/\varepsilon^{3/2}$ is the ion poloidal viscosity coefficient (Hirshman and Sigmar 1981), q is the safety factor, $\mu_{i\zeta}$ is the coefficient describing the ion toroidal or anomalous viscosity or friction with neutrals, $F^h_\theta = F^{th}_{e\theta} + F^{ch}_{e\theta}$, and $F^h_\zeta = F^{th}_{e\zeta} + F^{ch}_{e\zeta}$. Employing (4.1), we obtain the expression for the radial electric field from (3.3):

$$E_r \approx \frac{1}{e_i n_c}\frac{\partial p_c}{\partial r} + \frac{1}{c}\left[\frac{B_{\theta p} F^h_\zeta}{\mu_{i\zeta}} - B_{\varsigma p}\left(1.17\,U_{Ti} + \frac{F^h_\theta}{\mu_{i\theta}}\right)\right]. \tag{4.2}$$

Drift effects are neglected in the following discussion, and, for this reason, we ignore the terms $\partial p_c/\partial r$ and U_{Ti} in the expression (4.2) for the radial electric field.

Substituting this result into (3.1) and (3.2), we find from (3.1), (3.2), and (3.6),

$$U^c_{e\zeta} \approx U^c_{i\zeta} + \frac{F^{ch}_{e\zeta}}{n_c \nu_{ei} M_e} - \frac{n_t}{n_c}\frac{\nu_{ee}+\nu_{ei}}{\nu_{ei}}\frac{B_{\zeta p}}{B_{\theta p}}\frac{F^h_\theta}{\mu_{i\theta}}. \tag{4.3}$$

Consequently, we estimate the current

$$j_\zeta = \sum_\alpha e_\alpha n_\alpha U^c_{\alpha\zeta} + \sum_\alpha e_\alpha n_\alpha U^t_{\alpha\zeta}$$

in the 'classical' case:

$$j_\zeta \approx \frac{e_e}{\nu_{ei} M_e}\left(F^{ch}_{e\zeta} - K\frac{\varepsilon}{q}\sqrt{\frac{M_e}{M_i}}F^h_\theta\right), \tag{4.4}$$

where K is a coefficient defined below. The last term on the right-hand side of (4.4) appears as a result of circulating-electron dragging by banana particles drifting in E_r and $B_{\theta p}$ cross-fields (such an interpretation has been suggested by Kolesnichenko et al. 1990). It is interesting to note that this term is similar to the term accounting for the bootstrap-like mechanism of AW current drive (Tsypin et al. 2000). However, Tsypin et al. (2000) did not consider the last effect. Nevertheless, in general, both these effects should be treated as equally important. They could substantially

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contribute to the total AW current drive in the presence of an ion banana orbit squeezed by the radial electric field (Tsypin et al. 2000). Therefore, the coefficient $K > 1$ takes into account both the effects of electron dragging and the bootstrap-like mechanism of AW current drive. Owing to the strong sheared radial electric field, the coefficient K should include the squeezing parameter S as well,

$$S = 1 - \frac{e_i B_{\zeta p}^2}{M_i \omega_{ci}^2 B_{\theta p}^2} \frac{dE_r}{dr}; \tag{4.5}$$

i.e., one should change $K \to K|S|^{3/2}$, since, in this case, the ion viscosity has the form $\mu_{i\theta} \approx 1.1 M_i n_c q^2 \nu_{ii}/(\varepsilon|S|)^{3/2}$ (see e.g. Berk and Galeev 1967; Shaing and Hazeltine 1992).

5. Estimates

As can be seen from (4.4), the second term in the parentheses is more important than the first, corresponding to the conventional AW current drive, under the inequality (in the case $|S| > 1$)

$$K_1 \left(\frac{k_\parallel}{k_\theta} \frac{B_{\theta p}^2}{B_{\varsigma p}^2} \right)^{2/3} < \frac{e_i \phi}{T_i} \frac{\rho_i^2}{\Delta r^2}, \tag{5.1}$$

where we have used $E_r = -d\phi/dr$, ϕ is the quasistationary electric field potential, $\rho_i^2 = v_{Ti}^2/\omega_{ci}^2$ is the ion Larmor radius, $v_{Ti}^2 = 2T_i/M_i$ is the square of the ion thermal velocity, $\Delta r = (d \ln \phi/dr)^{-1}$ is the characteristic length of the spatial variations of the electrostatic potential, and K_1 is a coefficient with $1 \leqslant K_1 < 10$. We have also taken into account that, according to (2.3), the ratio $F_{e\zeta}^{ch}/F_\theta^h$ is approximately equal to $k_\parallel/k_\theta$. To find the coefficient K_1 in (5.1) explicitly (like the coefficient K in (4.4)), it is necessary to use a more exact system of starting equations than that given by the model (3.1)–(3.11). This will be the topic of a forthcoming paper. The inequality (5.1) can be fulfilled in tokamak plasmas with a strong radial shear of the radial electric field (Shaing and Hazeltine 1992).

Let us consider the well-known characteristic relaxation times τ_θ and τ_ζ of poloidal and toroidal plasma rotation, respectively, in tokamaks:

$$\tau_\theta \approx \frac{q^2 n_c M_i}{\mu_{i\theta}} \approx \frac{\varepsilon^k}{\nu_{ii}}, \qquad \tau_\zeta \approx \frac{n_c M_i}{\mu_{i\zeta}} \tag{5.2}$$

(see the discussion by Morris et al. (1996) of the coefficient k in (5.2)). According to numerous experiments in axially symmetric tokamaks, the relaxation time τ_ζ is of the order of the characteristic energy confinement time τ_E (see e.g. one of the first confirmations of this scaling by Brau et al. 1983). Therefore, one can assume the inequality $\tau_\zeta \gg \tau_\theta$. Equations (4.2) and (4.4) were obtained under the assumption that the characteristic time τ of plasma processes satisfies the inequality $\tau > \tau_\zeta, \tau_\theta$. However, there are plasma processes that take place with $\tau_\zeta > \tau > \tau_\theta$, which was the regime considered by Kolesnichenko et al. (1990) in their calculation of the radial electric field and current drive by AWs. This corresponds to assuming a quasistationary poloidal and an arbitrary toroidal rotation of the plasma, so that the equation for the relaxation of toroidal rotation does not have to be considered. In this case, (3.1), (3.2), and (3.5) for trapped particles have the following solution for the radial electric field:

$$E_r \approx \frac{B_{\theta p}}{c}\left(U_{i\zeta}^c + \sqrt{\frac{M_e}{M_i}}\frac{F_{e\zeta}^{th}}{n_t \nu_{ei} M_e}\right). \tag{5.3}$$

This transitional radial electric field can substantially exceed the quasistationary electric field (4.2).

Analyzing (4.2) and (5.3), one sees that the radial electric field induced by AWs in a tokamak plasma depends on the RF forces $\boldsymbol{F}_e^{ch}$ and $\boldsymbol{F}_e^{th}$ affecting both circulating and trapped particles, respectively (see (2.3)). As has been mentioned above, estimates valid on conventional tokamaks show that $\boldsymbol{F}_e^{ch} < \boldsymbol{F}_e^{th}$. Thus, the radial electric field E_r is mainly produced due to AW absorption by trapped electrons. This important result constitutes one of the main contribution of this work.

Equation (4.4) recovers the well-known expression for AW current drive by RF power absorbed by circulating particles (Kolesnichenko et al. 1990; Elfimov et al. 1992), with an additional new term. This term depends on the friction between circulating and trapped particles due to the drift in the E_r and $B_{\theta p}$ cross-fields. This term is similar to that obtained previously for the bootstrap-like mechanism of AW current drive (Tsypin et al. 2000), and can be substantial in the case of a strongly sheared radial electric field. This constitutes a secondary but certainly relevant result of this work.

We should like to underscore that plasma rotation induced by AWs in a tokamak has been clearly demonstrated in experiments on the Phaedrus-T tokamak (Wukitch et al. 1996). The value of the induced toroidal velocity in these experiments was at the level of or higher than that of plasma diamagnetic drift velocities, for absorbed power $P_w < 1\,\mathrm{W\,cm^{-3}}$. Unfortunately, no direct estimates were obtained of the corresponding radial electric field E_r induced by AWs in these experiments. Also, no attempts have been made to observe possible suppression of plasma turbulent activity by this radial electric field, corresponding to the transport barriers and improved confinement observed in tokamaks. In forthcoming experiments on the Tokamak Chauffage Alfvén Brazilian (TCABR) (Galvão et al. 1999), the absorbed power P_w of AWs is expected to be higher than that in the above-mentioned experiments, i.e. $P_w > 1\,\mathrm{W\,cm^{-3}}$. The estimates obtained by Tsypin et al. (1998, 1999) have shown that this absorbed power can induce a radial electric field E_r of the order of $10^2\,\mathrm{V\,cm^{-1}}$. This value is comparable to the radial electric field achieved in improved confinement experiments on the TFTR tokamak (Synakowski et al. 1997). These data give a hope of obtaining successful results on creating transport barriers on the TCABR tokamak.

6. Conclusions

In conclusion, we have shown that absorption of AWs by trapped particles can be rather beneficial for inducing sheared poloidal and toroidal rotation in tokamaks to maintain internal transport barriers. The radial electric field can be increased for characteristic times smaller than the characteristic time for relaxation of toroidal rotation but larger than that for poloidal rotation. Furthermore, it has also been shown that $\boldsymbol{E} \times \boldsymbol{B}$ drift in the radial electric field makes a positive contribution to the toroidal current driven by the AWs.

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References

Berk, H. L. and Galeev, A. A. 1967 Velocity space instabilities in a toroidal geometry. *Phys. Fluids* **10**, 441–450.

Biglari, H., Diamond, P. H. and Terry, P. W. 1990 Influence of sheared poloidal rotation on edge turbulence. *Phys. Fluids* **B2**, 1–4.

Braginskii, S. I. 1965 Transport processes in plasma. In: *Reviews of Plasma Physics*, Vol. 1 (ed. M. A. Leontovich). New York: Consultants Bureau, pp. 205–309.

Brau, K., Bitter, M., Goldston, R. J., Manos, D., McGuire, K. and Suckewer, S. 1983 Plasma rotation in the PDX tokamak. *Nucl. Fusion* **23**, 1643–1655.

Burrell, K. H. 1997 Effects of $\boldsymbol{E} \times \boldsymbol{B}$ velocity shear and magnetic shear on turbulence and transport in magnetic confinement devices. *Phys. Plasmas* **4**, 1499–1518.

Craddock, G. G. and Diamond, P. H. 1991 Theory of shear suppression of edge turbulence by externally driven radiofrequency waves. *Phys. Rev. Lett.* **67**, 1535–1538.

Elfimov, A. G., Kirov, A. G. and Sidorov, V. P. 1992 Alfvén wave heating and current drive. In: *High-Frequency Plasma Heating* (ed. A. G. Litvak). New York: American Institute of Physics Translation Series, pp. 239–280.

Galvão, R. M. O., Elfimov, A. G., Amarante-Segundo, G., Tsypin, V. S., Ruchko, L. F., Nascimento, I. C. and Tendler, M. 1999 Alfven wave heating, current drive, plasma flow and improved confinement scenarios in tokamaks. *Plasma Phys. Contr. Fusion* **41**, A487–A494.

Hirshman, S. P. and Sigmar, D. J. 1981 Neoclassical transport of impurities in tokamak plasmas. *Nucl. Fusion* **21**, 1079–1201.

Karney, C. F. F. and Fish, N. J. 1979 Numerical studies of current generation by radio-frequency traveling waves. *Phys. Fluids* **22**, 1817–1824.

Kolesnichenko, Ya. I., Parail, V. V. and Pereverzev, G. V. 1990 Noninductive current generation in tokamaks. In: *Reviews of Plasma Physics*, Vol. 17 (ed. B. B. Kadomtsev). New York: Consultants Bureau, pp. 3–156.

Morris, R. C., Haines, M. G. and Hastie, R. J. 1996 The neoclassical theory of poloidal flow damping in a tokamak. *Phys. Plasmas* **3**, 4513–4520.

Rosenbluth, M. N., Hazeltine, R. D. and Hinton, F. L. 1972 Plasma transport in toroidal confinement systems. *Phys. Fluids* **15**, 116–140.

Shaing, K. C. and Hazeltine, R. D. 1992 Effects of orbit squeezing on ion-transport in the banana regime in tokamaks. *Phys. Fluids* **B4**, 2547–2551.

Synakowski, E. J., Batha, S. H., Beer, M. A., Bell, M. G., Bell, R. E., Budny, R. V. et al. 1997 Roles of electric field shear and Shafranov shift in sustaining high confinement in enhanced reversed shear plasmas on the TFTR Tokamak. *Phys. Rev. Lett.* **78**, 2972–2975.

Tsypin, V. S., Elfimov, A. G., Nekrasov, F. M., de Azevedo, C. A. and de Assis, A. S. 1997 Current drive by Alfvén waves in elongated cross section tokamak. *Phys. Plasmas* **4**, 3635–3643.

Tsypin, V. S., Galvão, R. M. O., Nascimento, I. C., Elfimov, A. G., Tendler, M., de Azevedo, C. A. and de Assis, A. S. 1998 Ion transport in tokamak plasmas with ion banana orbits squeezed by Alfvén waves. *Phys. Rev. Lett.* **81**, 3403–3406.

Tsypin, V. S., Nascimento, I. C., Galvão, R. M. O., Elfimov, A. G., Amarante Segundo, G. S. and Tendler, M. 1999 Anomalous and neoclassical transport suppression by the radial electric filed, induced by Alfvén waves in tokamaks. *Phys. Plasmas* **6**, 3548–3553.

Tsypin, V. S., Nascimento, I. C., Galvão, R. M. O. and Kuznetsov, Yu. K. 2000 On the bootstrap-like mechanism of the radio frequency wave current drive in tokamaks. *Phys. Plasmas* **7**, 1060–1063.

Wukitch, S., Litwin, C., Harper, M., Parker, R. and Hershkovitz, N. 1996 Experimental observation of rf driven plasma flow in the Phaedrus-T tokamak. *Phys. Rev. Lett.* **77**, 294–297.