*Aust. J. Phys.*, 1995, **48**, 691–6

# Chirality-dependent Plasma Density Profile Changes from Helicon Wave Ponderomotive Forces

*V. Petržílka*[A] *and R. L. Dewar*

Department of Theoretical Physcis and Plasma Research Laboratory,
Research School of Physical Sciences and Engineering, Australian National University,
Canberra, ACT 0200, Australia.
[A] Permanent address: Institute of Plasma Physics, Czech Academy of Sciences,
Za Slovankou 3, P.O.B. 17, 182 11 Praha 8, Czech Republic.
email:vap@tokamak.ipp.cas.cz

*Abstract*

It is shown that nonresonant helicon-wave-induced transport may result in significant changes in the plasma density radial profile; this is illustrated using parameters appropriate to the cylindrical experiment BASIL and the toroidal experiment SHEILA. Whereas $m = +1$ helicon waves induce an inward-directed transport and change the density profile to a more centrally peaked one with a higher density on the axis, $m = -1$ helicon waves induce an outward-directed transport velocity and change the density profile to a hollow one. This may be the clue to the puzzle as to why $m = -1$ helicon waves are frequently difficult or impossible to excite, as the plasma column is effectively blown off to the discharge chamber walls by the ponderomotive force density of the waves with this chirality (sense of rotation of the wavevector with respect to the axial or toroidal magnetic field).

## 1. Introduction

The purpose of this contribution is to estimate changes in the plasma density radial profile due to ponderomotive forces exerted by large-amplitude helicon waves in some low temperature plasma experiments. The possibility of influencing radial transport by using RF waves was suggested by Klíma (1980) and further developed for a cylindrical two-fluid plasma model by Klíma and Petržílka (1980). Radio-frequency flux control has also been studied by Inoue and Itoh (1980) and Fukuyama *et al.* (1982). An enhanced transport associated with high-power lower-hybrid heating has been found by Sperling (1978), with toroidal effects being taken specifically into account by Antonsen and Yoshioka (1986). Transport influenced by RF fields has been found in experiments by Demirkhanov *et al.* (1981) and Kauschke (1992).

Plasma transport induced by helicon waves has been explored by Petržílka (1994). In a more general context, plasma transport induced by radio frequency (RF) waves has been discussed by Petržílka (1993) and in a recent paper by Elfimov *et al.* (1994).

As in Petržílka (1994) and Elfimov *et al.* (1994), we use two-fluid time-averaged magnetohydrodynamic equations (Klíma 1980) and again here consider a cylindrical plasma model. The parameters used in the computations are appropriate to the experimental devices BASIL (Schneider *et al.* 1993) and

0004-9506/95/040691$05.00

SHEILA (Blackwell *et al.* 1989) of the Australian National University, though the latter is a non-axisymmetric torus so our cylindrical analysis is not strictly applicable. Nevertheless, our calculations indicate that ponderomotive forces can be important in this experiment. Our results are relevant also for helicon wave plasma sources and in other cases when helicon waves are excited (Chen 1991, 1992; Loewenhardt *et al.* 1991; Boswell *et al.* 1982; Boswell 1984).

Although recent experiments (Ellingboe *et al.* 1994) indicate that significant resonant wave–particle interactions can occur due to high energy electrons accelerated by the helicon wave antenna, our use of a fluid model precludes analysis of this effect. Thus our results are most relevant in the collision-dominated regime.

## 2. Wave Induced Changes in Radial Plasma Density Profiles

Let us assume that when the RF field of a helicon wave is switched on, the plasma density changes from an initial profile $n_0(r)$ to a new profile $n(r)$. (This is a thought experiment of course, since in practice the helicon wave is involved in forming the plasma.) Let the initial (i.e. before RF switch-on) outward radial transport velocity $V_0$ be given by diffusion,

$$V_0 = -D\frac{dn_0}{dr}\,, \tag{1}$$

where $D = \eta T/B_0^2$ for the case where the diffusion is classical, $\eta$ is the plasma resistivity, $T$ is the temperature and $B_0$ is the magnetostatic field. For simplicity, the plasma temperature is assumed not to vary across the plasma column radius. After the RF is switched on, an additional transport velocity $V^{\mathrm{RF}}$ is induced, by the action of ponderomotive forces, which changes the steady-state average plasma density profile to a new one, and a new outward diffusion velocity

$$V = -D\frac{dn}{dr} \tag{2}$$

results. Thus the new total transport velocity is $V + V^{\mathrm{RF}}$, where

$$V^{\mathrm{RF}} = -\frac{1}{eB_0 n}\left(\frac{B_{0z}}{B_0}F_{\mathrm{e}\theta} - \frac{B_{0\theta}}{B_0}F_{\mathrm{e}z}\right). \tag{3}$$

For details of the calculation of $V^{\mathrm{RF}}$, the reader is referred to the papers by Petržílka (1994) and Elfimov *et al.* (1994). We use cylindrical coordinates $r, \theta, z$, and take averaging over the magnetic surface to be implicit, with $\boldsymbol{B}_0$ the magnetostatic field, $n$ the time averaged plasma density, and $\boldsymbol{F}$ the force density acting on the electron fluid due to the RF field.

This ponderomotive force density $\boldsymbol{F}_{\mathrm{e}}$ is given by

$$F_{\mathrm{e},z} = \sum \frac{k_z}{\omega}A_{\mathrm{e}}(r,m,k_z) - \tfrac{1}{2}\mathrm{Re}\left[\frac{1}{r}\frac{\partial}{\partial r}\left(rj_{\mathrm{e},r}(\frac{i}{\omega}E_z^* + \frac{j_{\mathrm{e},z}^*}{\epsilon_0\omega_{\mathrm{pe}}^2})\right)\right], \tag{4}$$

$$F_{\mathrm{e},\theta} = \sum \frac{m}{r\omega} A_{\mathrm{e}}(r, m, k_z) - \frac{1}{2r^2} \mathrm{Re}\left[\frac{\partial}{\partial r}\left(r^2 j_{\mathrm{e},r}\left(\frac{i}{\omega} E_\theta^* + \frac{j_{\mathrm{e},\theta}^*}{\epsilon_0 \omega_{\mathrm{pe}}^2}\right)\right)\right], \tag{5}$$

where $A_{\mathrm{e}}$ is the RF power density absorbed by electrons from the $(m, k_z)$ mode, $\omega_{\mathrm{pe}}$ is the Langmuir frequency, $j_{\mathrm{e},i}$ are the oscillating currents and $E_i$ denotes the oscillating electric field of the wave.

In the following, we consider the case of the helicon wave propagation governed by the cold plasma dielectric tensor $\epsilon_{ik}$ (Ginzburg 1960); we *do not* assume that the electron–ion collision frequency $\nu$ is smaller than the wave angular frequency $\omega$. We assume that Landau damping may be represented by an effective collision frequency $\nu_{\mathrm{LD}}$ (Chen 1991).

As the magnetostatic field intensity is much higher than that considered by Harvey and Lashmore-Davies (1993), the cyclotron damping is negligible in the range of plasma densities about $1 \times 10^{19}$ m$^{-3}$, which we assume in the following computations. The collisonal damping is approximately equal to Landau damping. The momentum dissipated by the higher velocity particles and subsequently in the bulk plasma due to the Landau damping is directed along the magnetostatic field, and thus contributes to the force $F_{\mathrm{e},z}$ given by equation (4). However, in the following computations the dominant term in the equation for $V^{\mathrm{RF}}$ is the term proportional to $F_{\mathrm{e},\theta}$. It means that the effects of Landau damping and of the poloidal magnetostatic field on the computations of the RF field induced changes in the plasma density profiles are small.

Before switching on the RF field, or before the RF induced transport velocity begins to compete with the plasma transport velocity given by diffusion, the stationary profile of the plasma density is given by

$$\mathrm{div}(n_0 V_0) = \frac{1}{r}\frac{\partial}{\partial r}(r n_0 V_0) = Q_0\,, \tag{6}$$

where $V_0$ is given by equation (1) and $Q_0$ represents plasma sources and sinks.

Let us assume that the RF field induces a transport velocity $V^{\mathrm{RF}}$, in addition to the velocity $V_0$, together with a change $\delta n$ in the plasma density, where $\delta n$ may be comparable to $n$. The modified plasma density $n$ is given by the equation $n = n_0 + \delta n$. Then, by using equation (2), we obtain from equation (6) the diffusion equation

$$\frac{\partial}{\partial r}\left[r(n_0 + \delta n)\left(V^{\mathrm{RF}} - D\frac{\partial(n_0 + \delta n)}{\partial r}\right)\right] = Q\,, \tag{7}$$

where $Q$ represents plasma sources and sinks, which might be changed by the presence of the RF field.

Assuming that the sources in (7) are not changed significantly by variations in RF power, then $Q = Q_0$, which may be reasonable for the highly ionised plasma in SHEILA and BASIL, we obtain from the diffusion equation the following differential equation for the plasma density $n(r)$,

$$Dn\frac{d(n-n_0)}{dr} = nV^{\mathrm{RF}} + V_0(n-n_0)\,. \tag{8}$$

This equation is, together with (3) for $V^{\mathrm{RF}}$, the basis of our estimates of the effects of RF fields on the plasma density profile.

It is important to note that the RF induced transport velocity $V^{\mathrm{RF}}$ given by (3) may change sign in its dependence on plasma and RF wave parameters, as described by Elfimov *et al.* (1994) and Petržílka (1994). Typically, for $m=1$ helicons, the velocity $V^{\mathrm{RF}}$ is negative, directed into the plasma interior. On the other hand, for $m=-1$ helicons, the velocity $V^{\mathrm{RF}}$ is positive, and thus contributes to the diffusion velocity $V$.

## 3. Computational Results

The radial profiles of the electric fields have been taken according to Chen (1991), where a homogeneous plasma density profile was assumed. According to Chen and Light (1993), Blackwell *et al.* (1993) and Light and Chen (1993), the wave field profile for a centrally peaked plasma profile does not differ strongly from the wave profile in a homogeneous plasma cylinder. So the wave profiles we use may be a good first approximation for the case when the effects of ponderomotive forces result in steeper centrally peaked plasma density profiles. However, use of these wave field profiles in computations of $V^{\mathrm{RF}}$ might be a questionable approximation, when the initial plasma density profile changes under the action of ponderomotive forces of $m=-1$ helicon waves to a hollow plasma density profile.

It is further assumed that the mutual influence of collisions between electrons and neutral particles may be neglected in comparison with the effects of electron–ion collisions. The degree of ionisation in the SHEILA and BASIL experiments is usually high enough so that this condition is not violated. The effective collision frequency representing the Landau damping was put equal to zero for simplicity, though at densities of about $1\times10^{19}$ m$^{-3}$, used in the following computations, the Landau damping may be comparable to collisional damping. Nevertheless, at these relatively high densities, the energy of resonant particles would be quickly dissipated in the bulk plasma. The higher dissipation rate we therefore simulated by higher electric fields of helicon waves, to obtain the observed values of dissipation. This is equivalent to increasing the collision frequency to a higher effective one.

The computations of density profiles according to (8) were performed for a plasma radius of 3·5 cm, temperature of 5 eV, magnetostatic field of 0·1 T, wave frequency of 7 MHz and a parabolic density profile of $n_0(r)$, with boundary density of $1\times10^{18}$ m$^{-3}$, and central density of $1\cdot1\times10^{19}$ m$^{-3}$. These parameters are characteristic of the SHEILA and BASIL experiments. The poloidal magnetostatic field was assumed to be one third of the main toroidal field, and negative, as in SHEILA. For computations of the dissipated power, a cylinder of length $2\pi\times19\cdot5$ cm was assumed, 19·5 cm being the SHEILA major radius.

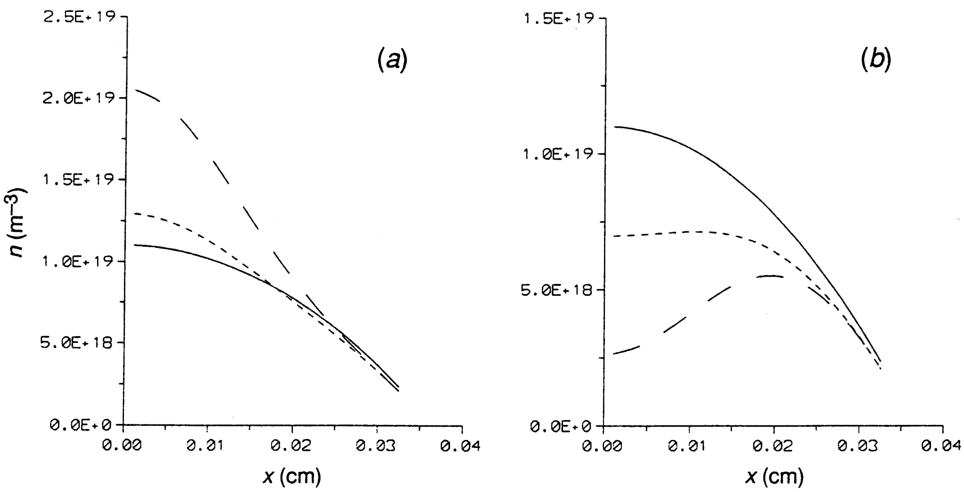


**Fig. 1.** Plasma density profiles for ($a$) $m = +1$ and ($b$) $m = -1$ helicons. The solid curves correspond to zero RF power, the short-dashed curves to intermediate power and the long-dashed curves to high power.

The computation proceeded in iterations, in which the new density profile and then the corresponding new $V^{\mathrm{RF}}$ is computed in each step, corresponding to the new value of the plasma density averaged over the minor radius. The computational results are presented in Fig. 1 for $m = +1$ and for $m = -1$ helicon waves. The density profile $n_0(r)$ is represented by the solid curve. Curves with short and long dashes correspond to density profiles for lower and higher RF powers, respectively. In both parts, the lower dissipated power is 700 W, whereas the higher one is 2700 W in Fig. 1$a$ and 1700 W in Fig. 1$b$.

## 4. Discussion and Conclusion

As can be seen, higher RF power leads to higher central densities and steeper density profiles in the case of $m = +1$ helicon waves, whereas for $m = -1$ helicon waves, increasing the RF power results in lower central plasma densities and hollow profiles. For $m = -1$ helicon waves, a RF power of about 1700 W is the highest for which a solution of (8) can be found with a central density higher than zero in SHEILA or BASIL.

Effectively, the plasma is blown to the walls of the discharge chamber by the ponderomotive force of the $m = -1$ helicon waves. This may be the reason why these $m = -1$ helicon waves are frequently difficult or impossible to excite, cf. Chen and Light (1993), Blackwell *et al.* (1993) and Light and Chen (1993).

As in most theoretical treatments, our computations and conclusions were made possible through the omission of some physical processes. We have neglected the changes in the helicon wave fields because of the plasma inhomogeneity. This effect has been explored by Chen and Light (1993) and Light and Chen (1993). They come to the conclusion that the $m = +1$ mode may be easier to couple because of the large electric field area, while the $m = -1$ mode has a smaller electric field area. However, in contrast to our conclusions, they obtained from their computations a still higher peaking of the $m = -1$ discharge than they obtained for the $m = +1$ one. This theoretical conclusion (Chen and Light 1993) has not been confirmed by experiments (Light and Chen 1993).

As a better approximation for computing the changes in plasma density profiles due to ponderomotive forces, in addition to computing the new $V^{\mathrm{RF}}$ at each iteration step, the self-consistent change of the helicon wave field profile should also be computed. A numerical code implementing this is in preparation.

**Acknowledgments**

We are grateful to the referees for their useful comments. One of the authors (V.P.) gratefully acknowledges the kind hospitality of the Department of Theoretical Physics and the Plasma Research Laboratory, Research School of Physical Sciences and Engineering, Australian National University, and financial support from an Australian Research Council Queen Elizabeth II Fellowship research grant (Dr G. G. Borg) and from the Australian Government under the Bilateral Science and Technology Collaboration Program administered by the Department of Industry, Science and Technology.

**References**

Antonsen, T. M., Jr, and Yoshioka, K. (1986). *Phys. Fluids* **29**, 2235.
Blackwell, B. D., Hamberger, S. M., Sharp, L. E., and Shi, X.-H. (1989). *Aust. J. Phys.* **42**, 73.
Blackwell, D. D., Sudit, I. D., and Chen, F. F. (1993). *Bull. Am. Phys. Soc.* **38**, 1897.
Boswell, R. W. (1984). *Plasma Phys. Contr. Fusion* **26**, 1147.
Boswell, R. W., *et al.* (1982). *Phys. Lett.* A **91**, 163.
Chen, F. F. (1991). *Plasma Phys. Contr. Fusion* **33**, 339.
Chen, F. F. (1992). *J. Vac. Sci. Technol.* A **10**, 1389.
Chen, F. F., and Light, M. (1993). *Bull. Am. Phys. Soc.* **38**, 1897.
Demirkhanov, R. A., Kirov, A. G., Ruchko, and L. F., Sukachev, A. V. (1981). Proc. 10th EPS Conference on Plasma Physics and Controlled Fusion, Moscow, Vol. 1, E-7 (Sovincentr: Moscow).
Elfimov, A. G., Petržílka, V., and Tataronis, J. A. (1994). *Phys. Plasmas* **1**, 2882.
Ellingboe, A. R., Boswell, R. W., Booth, J. P., and Sadeghi, N. (1995). *Phys. Plasmas* in press.
Fukuyama, A., Itoh, S., and Itoh, K. (1982). *J. Phys. Soc. Jap.* **51**, 1010.
Ginzburg, V. L. (1960). 'Propagation of Electromagnetic Waves in Plasma' (in Russian) (GIFML: Moscow).
Harvey, B. M., and Lashmore-Davies, C. N. (1993). *Phys. Fluids* B **5**, 3864.
Inoue, S., and Itoh, K. (1980). Proc. 8th IAEA Conference on Plasma Physics and Controlled Fusion Research, Brussels, Vol. **2**, p. 649 (IAEA: Vienna).
Kauschke, V. (1992). *Plasma Phys. Contr. Fusion* **34**, 1303.
Klíma, R. (1980). *Czech. J. Phys.* B **30**, 874.
Klíma, R., and Petržílka, V. (1980). *Czech. J. Phys.* B **30**, 1002.
Light, M., and Chen, F. F. (1993). *Bull. Am. Phys. Soc.* **38**, 1897.
Loewenhardt, P. K., Blackwell, B. D., Boswell, R. W., Conway, G. D., and Hamberger, S. M. (1991). *Phys. Rev. Lett.* **67**, 2792.
Petržílka, V. (1993). *J. Plasma Phys.* **49**, 55.
Petržílka, V. (1994). *Aust. J. Phys.* **47**, 315.
Schneider, D. A., Blackwell, B. D., Borg, G. G., Boswell, R. W., and Zhang, B. C. (1993). Book of Abstracts, AINSE Conference, Canberra (Ed. R. L. Dewar), p. T-29 (ANU: Canberra).
Sperling, J. L. (1978). *Phys. Fluids* **21**, 221.

Manuscript received 21 October 1994, accepted 9 February 1995