August 1993 ANU-PRL-TP93/02

VARIATIONS OF HELICON WAVE INDUCED RADIAL PLASMA TRANSPORT IN DIFFERENT EXPERIMENTAL CONDITIONS

V. Petržílka

Department of Theoretical Physics and Plasma Research Laboratory,
Research School of Physical Sciences and Engineering,
The Australian National University,
Canberra, A.C.T. 0200, Australia
Permanent address: *Institute of Plasma Physics, Czech Academy of Sciences,*
Za Slovankou 3, P.O.B. 17, 182 11 Praha 8, Czech Republic
FP28@CSPGAS11.BITNET

Abstract. Variations of the helicon wave induced radial plasma transport are presented in dependence on values of the plasma radius, magnetostatic field, plasma density, frequency of the helicon wave and on the ion charge.

1 Introduction

The purpose of this contribution is to estimate variations of the helicon wave induced radial transport of plasma due to variations in the radius of the plasma cylinder, imposed magnetostatic field, plasma density, frequency of the transport driving helicon wave and the composition of the gas, i.e., the ion charge. First estimates of such helicon wave driven radial plasma transport are presented in a paper by Petržílka (1993b) together with radial profiles of the radio frequency (RF) driven transport. The possibility of influencing the radial transport by RF waves has been suggested by Klíma (1980); this idea has been further developed for a cylindrical two fluids plasma model by Klíma and Petržílka (1980). The radio frequency flux control has been studied also by Inoue and Itoh (1980) and

Fukuyama et al. (1982). An enhanced transport associated with the high power lower hybrid heating has been found by Sperling (1978), while specifically toroidal effects have been accounted for by Antonsen and Yoshioka (1986). The transport influenced by RF fields has been found in experiments by Demirkhanov et al. (1981) and Kauschke (1992). We use two fluids magnetohydrodynamic equations and consider here a cylindrical model of plasma (Petržílka, 1993a), which allows to obtain analytical expressions for ponderomotive forces and to elucidate the role of the poloidal magnetostatic field and of the wave polarization on the radial plasma transport. This theory is used for obtaining estimates of helicon wave induced radial plasma transport. However, the assumption that the collision frequency is much smaller than the wave frequency is not used here. The results are relevant for helicon wave plasma sources and also in other cases when helicon waves are excited (Chen, 1991 and 1992; Loewenhardt et al., 1991; Boswell, 1984).

2 Wave Induced Radial Transport Velocity

We assume the presence of a quasisteady field $\mathbf{E}_0$, $\mathbf{B}_0$ and an HF field $\mathbf{E}$, $\mathbf{B}$. Plasma consists of single charge ions, electrons and possibly neutral particles. Time averaged (over HF oscillations) distribution functions of charged particles, but not necessarily their derivatives with respect to particle velocities, do not differ strongly from Maxwellian distributions. The energy of the oscillating motion of particles is much less than their thermal energy; this condition is not necessary and may be weakened, see papers by Petržílka et al. (1991) and Petržílka (1991a, b). The frequency of Coulomb collisions of electrons with ions is much less than the electron cyclotron frequency. Ionization and recombination processes do not effect the oscillating motions. Under these assumptions, the quasisteady plasma state is governed by time averaged hydrodynamic equations, which were derived from the averaged kinetic equation (Klíma, 1980). These equations have been used for a study of effects of HF fields on diffusion and convection in a plasma column by Klíma and Petržílka (1980) assuming that all time averaged quantities are constant along the z- axis which coincides with the plasma column axis, magnetic surfaces of the magnetostatic field are concentric cylinders, values of the electron and ion temperature and plasma density do not depend strongly on the poloidal angle; these assumptions are used also in this paper. Then, the radial component of the time averaged plasma mass velocity $\mathbf{V}$ is given by the following equation, where all quantities are averaged over the magnetic surface [eq. (5. 2) of Klíma and Petržílka, 1980]

$$V_{\rm r} = -\frac{B_{0\theta}}{B_0}E_{\rm d} + \frac{1}{eB_0 n_0}\left(\frac{B_{0z}}{B_0}F_{\rm i\theta} - \frac{B_{0\theta}}{B_0}F_{\rm iz} + \frac{3n_0}{2\omega_{\rm ce}\tau_{\rm e}}\frac{\partial T_{\rm e}}{\partial r}\right) - \frac{\eta_\perp}{B_0^2}\frac{\partial p}{\partial r}. \quad (1)$$

We use cylindrical coordinates r, θ, z, the symbol of averaging over the magnetic surface is omitted, $\mathbf{B}_0$ is the magnetostatic field, n_0 the time averaged plasma density, $\mathbf{F}_{\rm i(e)}$ is the force acting on ions (electrons) given by the RF field, by collisional friction with neutral particles and by ionization and recombination [see eq. (2. 5) of (Klíma and Petržílka, 1980)], $\omega_{\rm ce(i)} > 0$ is the electron (ion) cyclotron frequency, $\nu_{\rm e(i)} = \tau_{\rm e(i)}^{-1}$ is the electron (ion) collision frequency, $T_{\rm e}$ is the electron temperature, $\eta_{\perp(\parallel)}$ is the perpendicular (parallel) resistivity and p is the plasma pressure. Alternatively, also the coordinate system with unit vectors $\mathbf{e}_r, \mathbf{e}_\chi = \mathbf{e}_\parallel \times \mathbf{e}_r, \mathbf{e}_\parallel = \mathbf{B}_0/B_0$ will be used.

As we study a stationary state, the forces $\mathbf{F}_{\rm i}$ and $\mathbf{F}_{\rm e}$ fulfill the following equation

$$F_{\rm i\parallel} - \mathbf{e}_\parallel.(\nabla.\mathbf{P}_{\rm i}^{\rm T}) = \mathbf{e}_\parallel.(\nabla.\mathbf{P}_e^{\rm T}) - F_{\rm e\parallel}, \quad (2)$$

where

$$\mathbf{P}_\alpha^{\rm T} = \mathbf{P}_\alpha + m_\alpha n_\alpha \mathbf{U}_\alpha \mathbf{U}_\alpha, \quad (3)$$

$\alpha = e, i$, the superscript T means total, $\mathbf{P}_\alpha$ is essentially the thermal pressure tensor, $n_0\mathbf{U}_\alpha$ is the time averaged particle flux density.

The ponderomotive forces $\mathbf{F}_{\rm i(e)}^{\rm P}$, which are parts of the forces $\mathbf{F}_{\rm i(e)}$, are given by the equation (3. 5) and (3. 6) of (Klíma and Petržílka, 1980),

$$F_{\alpha,z}^{\rm P} = \sum \frac{k_z}{\omega}A_\alpha(r, m, k_z) - \frac{1}{2}Re\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r j_{\alpha,r}(\frac{i}{\omega}E_z^* + \frac{j_{\alpha,z}^*}{\epsilon_0\omega_{p\alpha}^2})\right)\right], \quad (4)$$

$$F_{\alpha,\theta}^{\rm P} = \sum \frac{m}{r\omega}A_\alpha(r, m, k_z) - \frac{1}{2r^2}Re\left[\frac{\partial}{\partial r}\left(r^2 j_{\alpha,r}(\frac{i}{\omega}E_\theta^* + \frac{j_{\alpha,\theta}^*}{\epsilon_0\omega_{p\alpha}^2})\right)\right], \quad (5)$$

where $\alpha = i, e$, symbols denoting averaging over the polar angle θ are omitted, A_α is the RF power density absorbed by the given particle sort from the m, k_z mode, $\omega_{\rm p\alpha}$ is the Langmuir frequency, $j_{\alpha,\rm i}$ are the oscillating currents and $E_{\rm i}$ denotes the oscillating electric field of the wave.

In the following, we will consider the case of the wave propagation governed by the cold plasma dielectric tensor $\epsilon_{\rm ik}$ (Ginzburg, 1961); we *do not* assume that the electron-ion collision frequency ν is smaller than the wave angular frequency ω. Landau damping is represented by an effective collision frequency $\nu_{\rm LD}$ (Chen, 1991).

We further note that when

$$F_{i\parallel} \simeq -F_{e\parallel} \qquad (6)$$

which may easily be the case [cf. equation (5. 8) in Klíma and Petržílka, 1980], we may express V_r in terms of $F_{e\parallel}$ from equation (1) simply by substitution according to equation (6). Again, symbols of averaging over the polar angle θ are omitted in (6). In case the momentum imparted to the plasma by RF field is balanced by ions, e. g. , by collisions of neutrals with ions, the computation of V_r by means of $F_{e\parallel}$ may be more straightforward. In this case, to evaluate the RF field induced radial transport velocity as given by equation (1), we have to evaluate the ponderomotive forces, equations (4-5). For this purpose, we have expressed currents $j_{e,\beta}$ ($\beta = r, \theta, z$) in terms of oscillating electric fields for an arbitrary value of the collision frequency with respect to the wave frequency (see Appendix).

3 Computational Results

The radial transport velocity given by eq. (1) has been computed for various sets of parameters and corresponding curves are in Figs. 1–14. The radial profiles of the electric fields has been taken according to Chen (1991). However, Chen assumes that the wave frequency is greater than the lower hybrid frequency. This condition is not valid for some values of parameters used in the computations; this could influence namely the profiles of V_r, not estimates of its absolute value. Results of the computations presented in what follows indicate that the RF induced plasma diffusion may compete with the experimentally estimated plasma diffusion velocity (Boswell et al., 1982).

For the azimuthal wave number $m = 1$, estimates of the helicon wave induced radial transport velocity in hydrogen V_{RF} are presented in Figs. 1–5. The value of V_{RF} is taken always at the half of the plasma radius at $r = 0.5a$. For a better orientation as far the value of V_{RF} is concerned, the transport velocity V_{dif} corresponding to the classical diffusion (assuming a linear plasma density growth) is also depicted by dashed curves. In Fig. 1, the plasma radius a is varied from 1 to $4cm$, the other parameters being fixed: the magnetostatic field $B_0 = B_z = 0.03T$, the helicon wave frequency $f = 27MHz$, the electron temperature $T = 3eV$, the maximum helicon wave electric field E_r amplitude is $E_{max} = 2kV/m$, the ion charge $Z = 1$ (hydrogen) and the plasma density $n = 6 \times 10^{18} m^{-3}$ is assumed to be constant across the plasma cylinder. For singly ionized heavier gases, like argon, the RF induced transport velocity is almost the same for sets of parameters studied here. For doubly ionized gases, we have higher Z and therefore higher collision frequency, and the RF induced radial transport velocity V_{RF} has smaller chances to compete with the velocity of the classical diffusion. For m=1 helicons, the velocity V_{RF} is negative with the exception of a very small region near the plasma axis, Fig. 11 ($a = 1cm$, the other parameters the same as in Fig. 1).

In Fig. 2, the magnetostatic field is varied, $0.01 < B_0 < 0.05T$; it can be seen that for smaller magnetostatic fields the RF field induced diffusion may more easily prevail over the classical one.

In Figs 3–4, the plasma density n is varied. We see that for lower densities, V_{RF} may more easily have greater values than V_{dif}.

Figs. 5 shows that V_{RF} may be of importance more easily for lower helicon wave frequencies f.

For $m = 0$ helicons, dependences of V_{RF} on various parameters are depicted in Figs. 6–10 analogously to Figs. 1–5, respectively. We see that V_{RF} for $m = 0$ helicons is much smaller in its absolute value than V_{RF} induced by $m = 1$ helicons. The radial profile of V_{RF} for an $m = 1$ helicon is depicted in Fig. 11. Again, similarly as in Fig. 12 for an $m = -1$ and in Fig. 13 for both $m = 1$ and $m = -1$ helicons excited, the plasma radius a is $a = 1cm$, the other parameters being the same as in Fig. 1 or in Fig. 6.

4 Conclusion

It has been shown that $m = 1$ helicons contribute to the plasma confinement positively almost in the whole plasma volume with the exception of a very small region near the plasma cylinder axis. The opposite may be said as far $m = -1$ helicons are concerned. Helicons with the azimuthal wave number $m = 0$ induce much smaller V_{RF} with this velocity positive in the plasma interior and negative near the boundary, where they amend the confinement. So these helicons may support the creation of hollow discharges; however, the same about supporting hollow discharges may be said regarding $m = 1$ helicons. When $m = 1$ and $m = -1$ helicons are excited, the confinement is deteriorated namely in the plasma interior; again, hollow discharges might perhaps be created or their creation supported. The beneficent influence of the $m = 1$ helicons found here is in accordance with what has been found in experiments by Sato et al. (1983), Okamura et al. (1986).

The influence of the poloidal magnetostatic field B_θ on the RF induced transport has not been studied here, also the effective collision frequency ν_{LD} representing the Landau damping was put equal zero. For nonzero B_θ, the RF induced transport depends also on the direction of the wave propagation along the cylinder axis. Nonzero B_θ may be important for the RF induced transport namely for $\nu_{LD} > \nu$; in this case, the ponderomotive force directed along the plasma cylinder axis may be important for the RF induced transport.

Magnetostatic field values for which the RF induced transport may be observed are the lower ones used on the BASIL and SHEILA experiments at the Australian National University in Canberra assuming that the maximum helicon wave electric field amplitude is in the range of $1 - 2kV/m$.

We note that due to the simplifying assumption of $n = const$ the profiles of the RF induced transport velocity should be considered as the first approximation only. The important result of this work is that sets of parameters have been found, where the RF induced transport may be important. The next step should be computations of RF induced transport with realistic density profiles. Also wave electric field profiles should be measured and the result used as input data for computations.

Acknowledgment: The author gratefully acknowledges the kind hospitality of the Department of Theoretical Physics and the Plasma Physics Laboratory, Research School of Physical Sciences and Engineering, The Australian National University, and the financial support of the Department of Theoretical Physics and of the Australian Government under the Bilateral Science and Technology Collaboration Program administered by the Department of Industry, Technology and Rural Development.

5 Appendix

The electric current density $\mathbf{j}_e$ is expressed by means of the oscillating electric field $\mathbf{E}$,

$$j_{e,i} = \sigma_{ik} E_k \tag{7}$$

where

$$\sigma_{xx} = h_1(h_2 b + h_3 a)$$
$$\sigma_{xy} = h_1(h_3 b - h_2 a)$$
$$\sigma_{zz} = i\epsilon_0 \frac{\omega\omega_{pe}^2}{\omega^2\left[1 - (\nu + \nu_{LD})/i\omega\right]} \tag{8}$$

and where further

$$h_1 = \frac{\epsilon_0\omega_{pe}^2}{a^2 + b^2}$$
$$h_2 = x_3 x_4 \omega_{ci}$$
$$h_3 = 1 + i x_3 x_4 \omega_\nu$$

$$
\begin{aligned}
a &= -i\omega + x_1\nu + ix_2x_4\nu\omega_\nu \\
b &= -\omega_{ce} + x_2x_4\nu\omega_\nu \\
x_1 &= 1840A/(1+1840A) \\
x_2 &= Zx_1^2/(1840A) \\
x_3 &= Z/(1+1840A) \\
x_4 &= \nu/(\omega_{ci}^2 - \omega_\nu^2) \\
\omega_{pe} &= (ne^2/(m_e\epsilon_0))^{0.5} \\
\omega_{pi} &= \omega_{pe}(Z/(1840A))^{0.5} \\
\omega_{ce} &= eB_0/m_e \\
\omega_{ci} &= Z\omega_{ce}/(1840A)
\end{aligned}
\qquad (9)
$$

Z is the ion charge, A is the atomic number, m_e is the electron mass, $e > 0$ is the absolute value of the electron charge.

6 Figure Captions

Fig. 1: Variations in the helicon $m = 1$ wave induced radial transport velocity when the plasma radius a is varied.
Fig. 2: Variations in the helicon $m = 1$ wave induced radial transport velocity when the magnetostatic field B_0 is varied.
Fig. 3: Variations in the helicon $m = 1$ wave induced radial transport velocity when the plasma density n is varied.
Fig. 4: Variations in the helicon $m = 1$ wave induced radial transport velocity when the plasma density n is varied.
Fig. 5: Variations in the helicon $m = 1$ wave induced radial transport velocity when the wave frequency f is varied.
Figs. 5 - 10: The same as in Figs. 1 -5, respectively, but for $m = 0$ helicons.
Fig. 11. The radial profile of the RF induced transport velocity for $m = 1$ helicons, other parameters being the same as in Fig. 1.
Fig. 12. The radial profile of the RF induced transport velocity for $m = 0$ helicons, other parameters being the same as in Fig. 1.
Fig. 13. The radial profile of the RF induced transport velocity for $m = -1$ helicons, other parameters being the same as in Fig. 1.
Fig. 14. The radial profile of the RF induced transport velocity for $m = 1$ and $m = -1$ helicons excited, other parameters being the same as in Fig. 1.

7 Refere

Antonsen T. M
Boswell R. et
Boswell R. W.
Chen F. F. (19
Chen F. F. (19
Demirkhanov
in Proc. of the
Moscow, Vol. *1*
Fukuyama A.
Ginzburg V.
Russian), GIFM
Inoue S. and I
Physics and Con
Kauschke V. (
Klíma R. (198
Klíma R. and
Loewenhardt
Hamberger S.
Okamura S. et
Petržílka V. (1
Petržílka V. (
Drive (publishe
Becoulet), Arles
Petržílka V.,
R. (1991) Nucl.
Petržílka V. (1
Petržílka V. (1
Sato T. et al.
Sperling J. L.

7 References

Antonsen T. M., Jr., and Yoshioka K. (1986) Phys. Fluids *29*, 2235.

Boswell R. et al. (1982) Physics Letters *91*A, 163.

Boswell R. W. (1984) Plasma Physics Contr. Fusion *26*, 1147.

Chen F. F. (1991) Plasma Physics Contr. Fusion *33*, 339.

Chen F. F. (1992) J. Vac. Sci. Technol. A*10*, 1389.

Demirkhanov R. A., Kirov A. G., Ruchko L. F., Sukachev A. V. (1981), in Proc. of the 10th EPS Conference on Plasma Physics and Controlled Fusion, Moscow, Vol. *1*, E-7.

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.

Inoue S. and Itoh K. (1980), in Proc. of the 8th IAEA Conference on Plasma Physics and Controlled Fusion Research, Brussels, Vol.*2*, p. 649.

Kauschke V. (1992) Plasma Physics 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.

Loewenhardt P. K., Blackwell B. D., Boswell R.V., Conway G.D. and Hamberger S.M. (1991) Phys. Rev. Letters *67*, 2792.

Okamura S. et al. (1986) Nucl. Fusion *26*, 1491.

Petržílka V. (1991a) Plasma Physics Controlled Fusion *33*, 365.

Petržílka V. (1991b) In Proc. of the IAEA Meeting on Fast Wave Current Drive (published by CEA Cadarache, edited by D. Moreau, Y. Peysson and A. Becoulet), Arles, September 1991, p. 190.

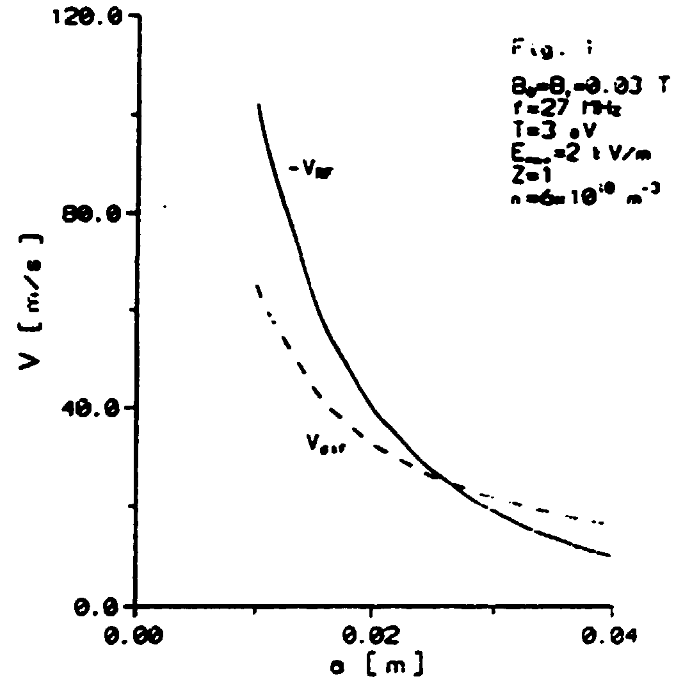
Petržílka V., Leuterer F., Soeldner F. X., Giannone L. and Schubert R. (1991) Nucl. Fusion *31*, 1758.

Petržílka V. (1993a) Journal of Plasma Physics, accepted for publication.

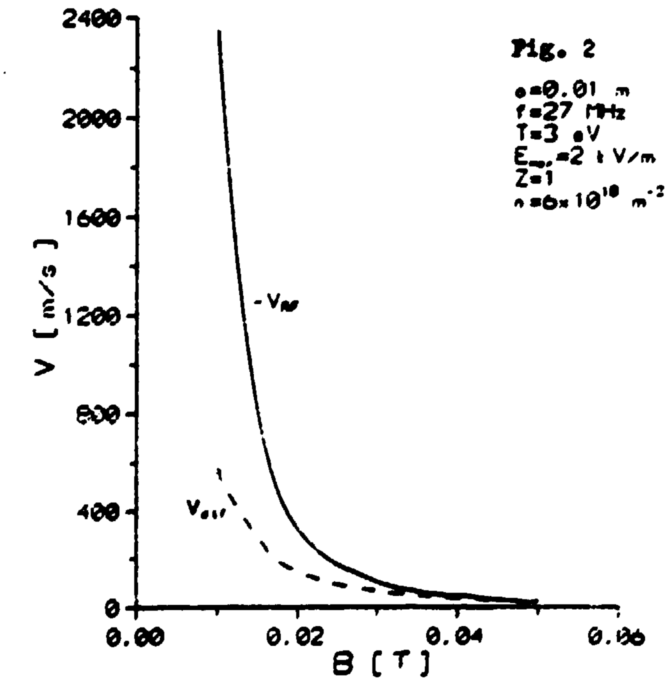
Petržílka V. (1993b) Czech. J. Phys. *43*, accepted for publication.

Sato T. et al. (1983) Nagoya University IPP Report IPPJ-653.

Sperling J. L. (1978) Phys Fluids *21*, 221.

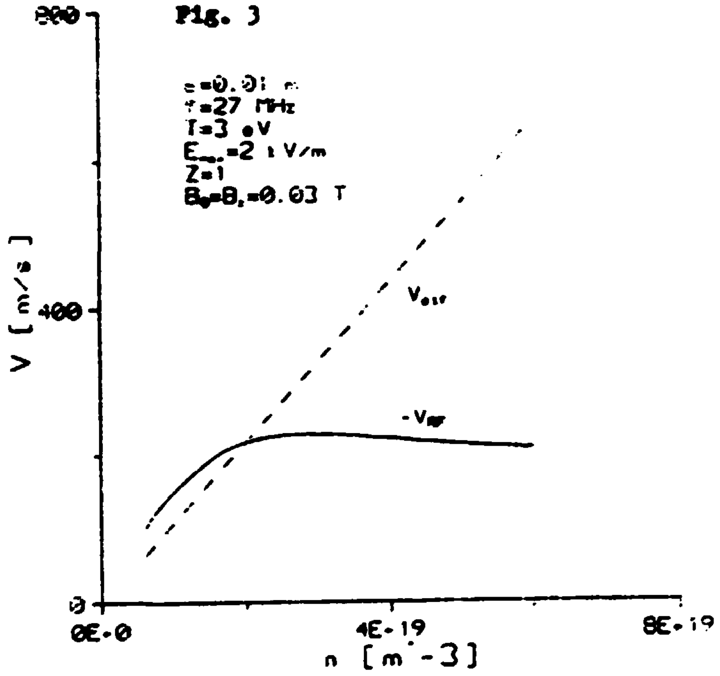


120.0
80.0
40.0
0.0
0.00
0.02
0.04
V [m/s]
a [m]
-V_RF
V_eff
Fig. 1
f=27 MHz
T=3 eV
Z=1



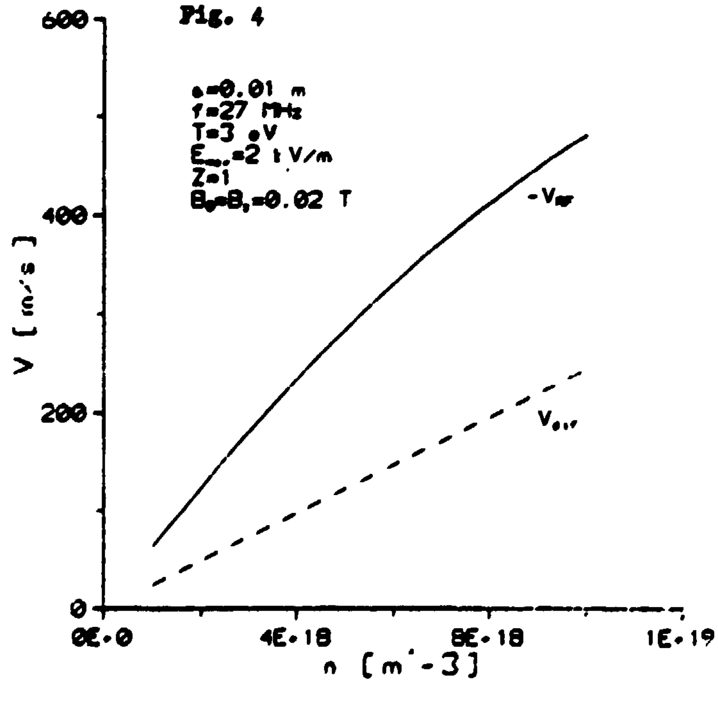
2400
2000
1600
1200
800
400
0
0.00
0.02
0.04
0.06
V [m/s]
B [T]
-V_RF
V_eff
Fig. 2
a=0.01 m
f=27 MHz
T=3 eV
Z=1

Fig. 3

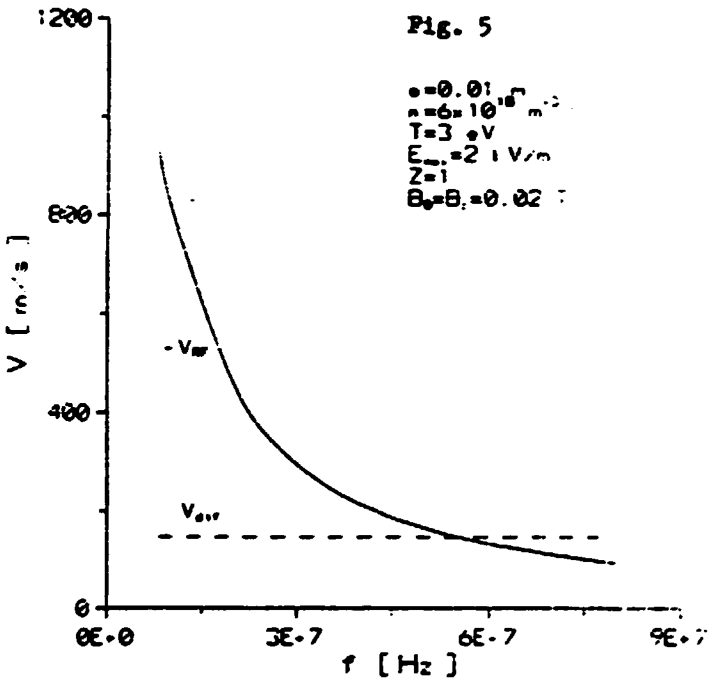


a=0.01 m
f=27 MHz
T=3 eV
Z=1
B=B=0.03 T
V [m/s]
400
0
0E+0
4E+19
8E+19
n [m^-3]

Fig. 4

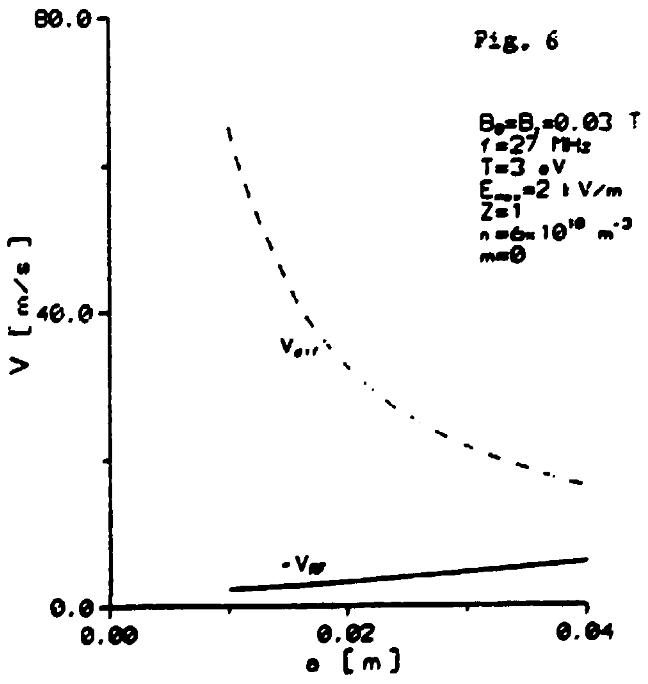


a=0.01 m
f=27 MHz
T=3 eV
Z=1
B=B=0.02 T
V [m/s]
600
400
200
0
0E+0
4E+18
8E+18
1E+19
n [m^-3]



1200
800
400
0
V [m/s]
-V_pf
V_dif
0E+0
3E-7
6E-7
9E+7
f [Hz]
T=3 eV
Z=1

Fig. 5



80.0
40.0
0.0
V [m/s]
V_dif
-V_pf
0.00
0.02
0.04
a [m]
f=27 MHz
T=3 eV
Z=1
m=0

Fig. 6

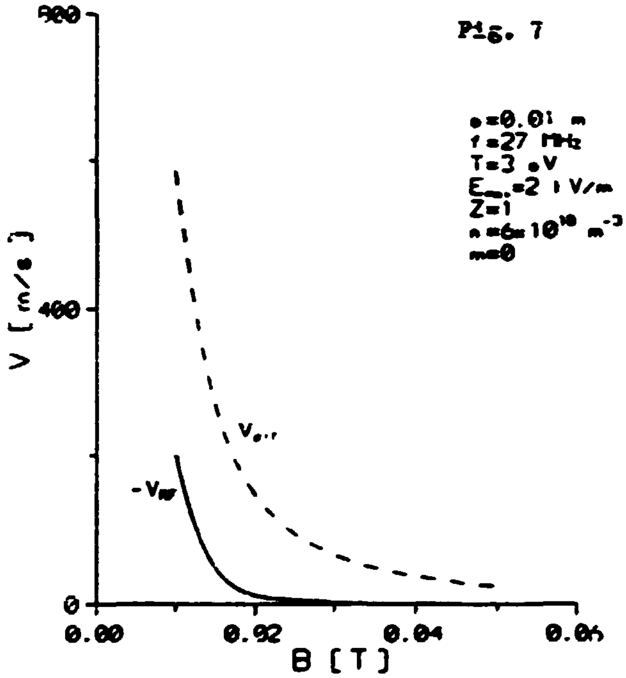

a=0.01 m
f=27 MHz
T=3 eV
Z=1
m=0
V [m/s]
B [T]
0
400
0.00
0.02
0.04
0.06

Fig. 7

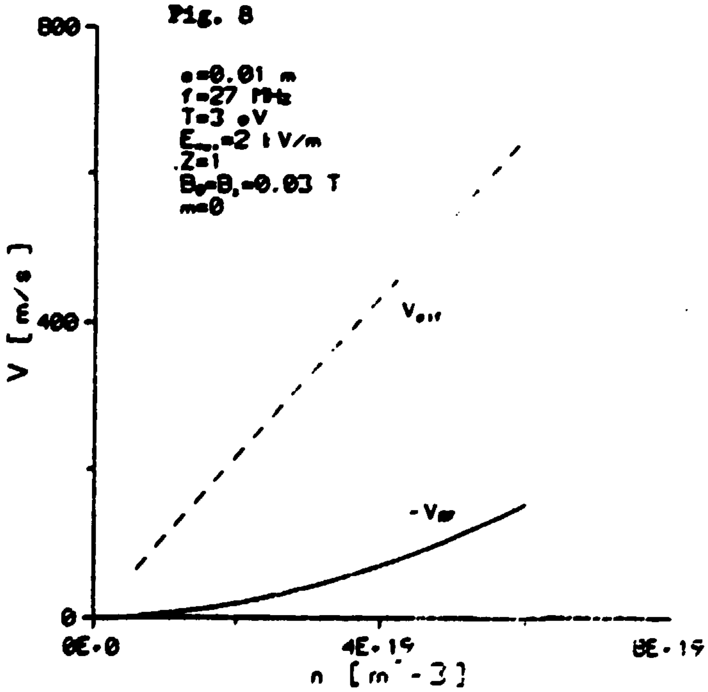
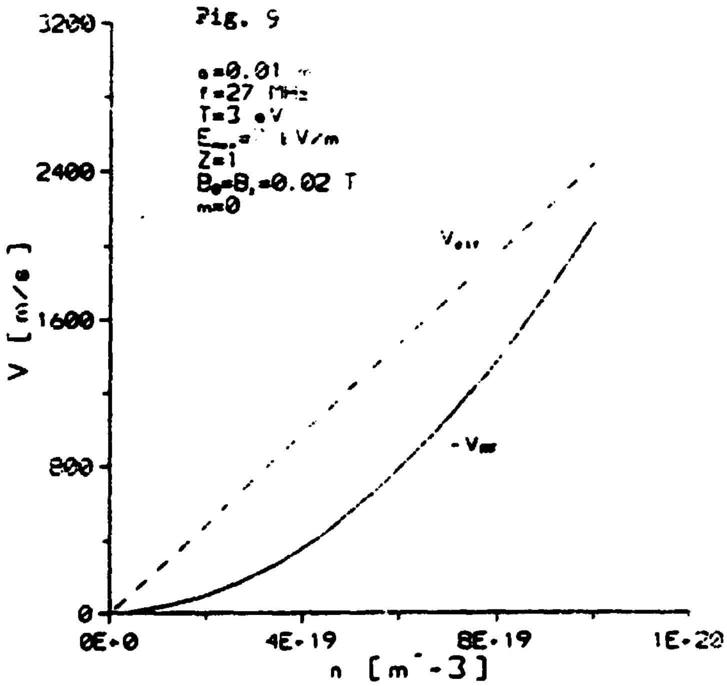
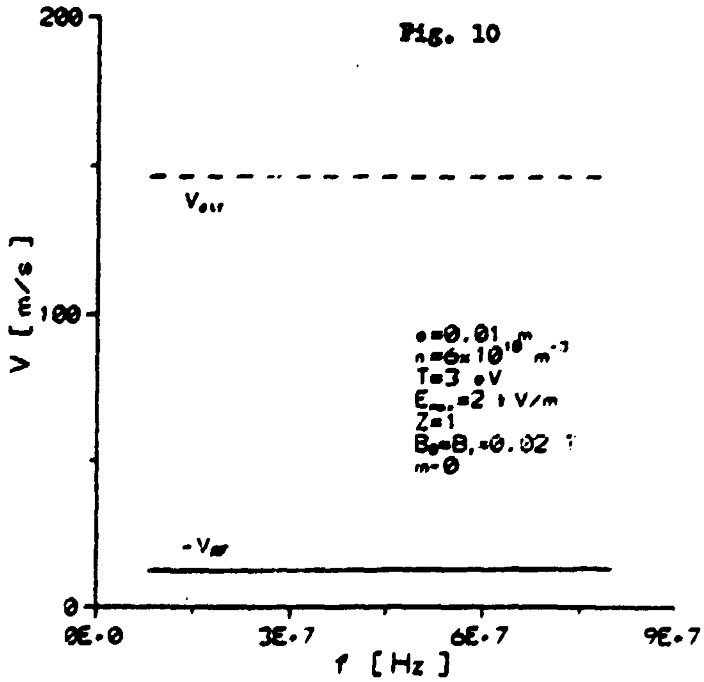

a=0.01 m
f=27 MHz
T=3 eV
Z=1
B=0.03 T
m=0
V [m/s]
n [m^-3]
0
400
800
0E+0
4E+19
8E+19

Fig. 8



3200
2400
1600
800
0
V [m/s]
a=0.01 m
f=27 MHz
T=3 eV
Z=1
B0=B1=0.02 T
m=0
Vex
-Vp
0E+0
4E+19
8E+19
1E+20
n [m^-3]

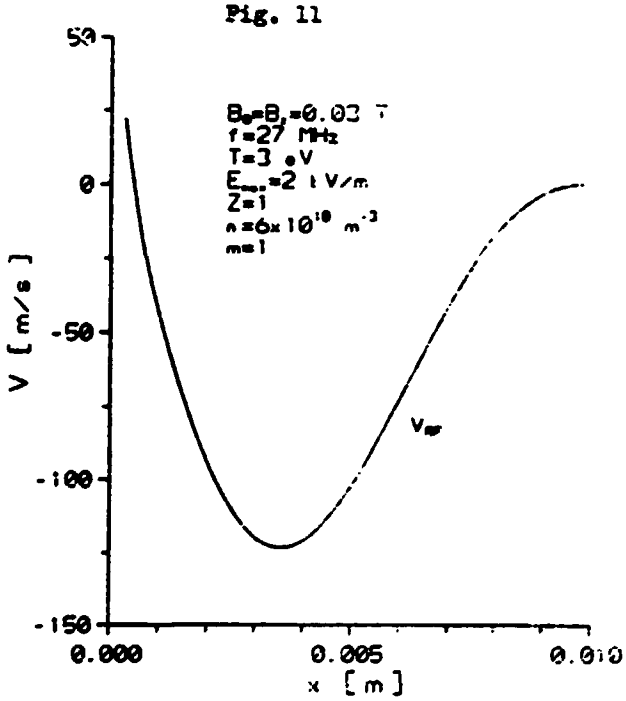
Fig. 9



200
100
0
V [m/s]
Vex
a=0.01 m
n=6x10^18 m^-3
T=3 eV
Emax=2 kV/m
Z=1
B0=B1=0.02 T
m=0
-Vp
0E+0
3E+7
6E+7
9E+7
f [Hz]

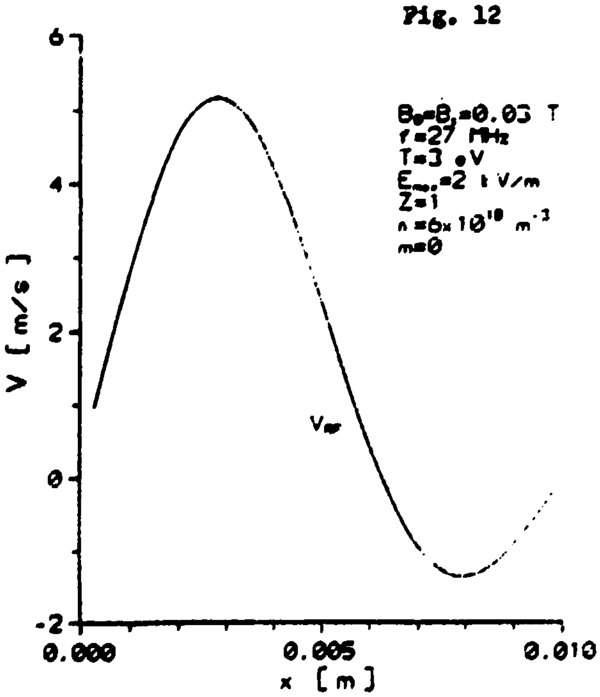
Fig. 10

Pig. 11



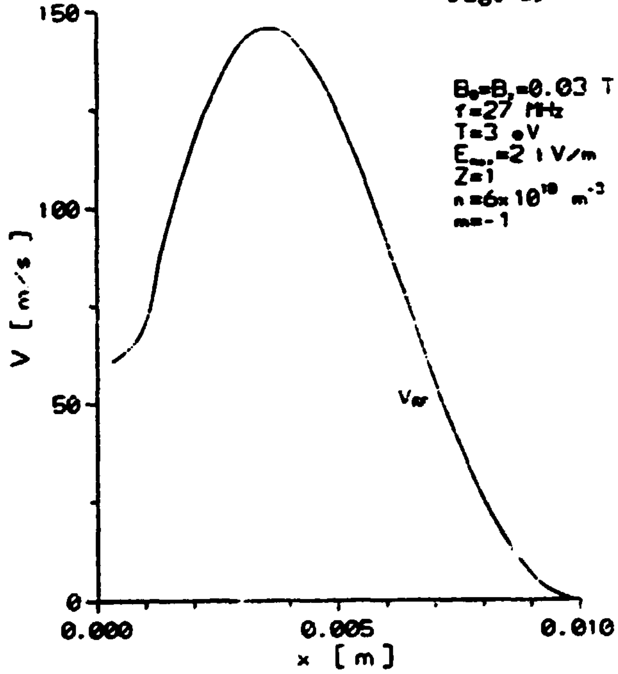
50
0
-50
-100
-150
0.000
0.005
0.010
x [m]
V [m/s]
$B_\theta = B_z = 0.03$ T
f=27 MHz
T=3 eV
E_{max}=2 kV/m
Z=1
n=6x10^{18} m^{-3}
m=1
$V_{\theta r}$

Pig. 12



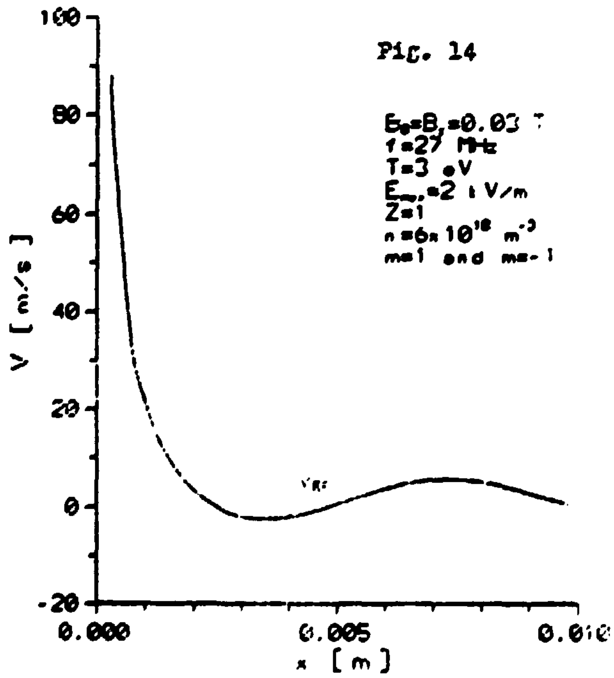
6
4
2
0
-2
0.000
0.005
0.010
x [m]
V [m/s]
$B_\theta = B_z = 0.03$ T
f=27 MHz
T=3 eV
E_{max}=2 kV/m
Z=1
n=6x10^{18} m^{-3}
m=0
$V_{\theta r}$

Fig. 13



f=27 MHz
T=3 eV
Z=1
m=-1
0.000
0.005
0.010
x [m]
V [m/s]
150
100
50
0

Fig. 14



f=27 MHz
T=3 eV
Z=1
m=1 and m=-1
0.000
0.005
x [m]
V [m/s]
100
80
60
40
20
0
-20