COLLISIONAL DEPOLARIZATION IN ARBITRARY MAGNETIC FIELDS

S. C. Cowley, R. M. Kulsrud

Plasma Physics Laboratory, Princeton University

P.O. Box 451

Princeton, New Jersey 08544

PPPL--2240

DE85 017681

ABSTRACT

The effect of arbitrary magnetic confinement geometry on the spin polarization of magnetically confined plasmas is investigated. The plasma is assumed to be in equilibrium so that the dominant depolarization mechanism is decorrelation of the spin-precession phase and the gyrophase by collisions.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

ef

INTRODUCTION

In a recent report (PPPL-2119) [1], we developed a kinetic theory for spin-polarized plasmas and applied it to some simple depolarization mechanisms. In Section 4.3 of that report, we investigated the effect of coulomb collisions in a model sheared magnetic field. In this report we generalize the result of that section to arbitrary magnetic fields. The new result is qualitatively the same as the previous result, i.e., in TFTR the depolarization time is 4,000 seconds. This report is to be viewed as an additional appendix to PPPL-2119. We will work in the guiding-center expansion where nonadiabatic effects are absent [2].

The physical process can be explained briefly as follows. The gyrating particle "sees" a magnetic field perpendicular to the mean field of order $B\rho_1|db/dx|$. In the frame of the gyrating particle, this magnetic field oscillates at the gyrofrequency Ω_C . The spin of an individual spin 1/2 particle is represented by the expectation value of the spin, the vector $\underline{p}$ [1]. The $\underline{p}$ vector [1] component perpendicular to the mean magnetic field, $\underline{p}_1$, rotates around the mean field at the precessional frequency Ω_p . For a time $(\Omega_C - \Omega_p)^{-1}$, the oscillating field will increase $[\underline{p}_1(\Delta p_1 \sim \rho_1 \Omega_p \rho_1 |db/dx| \Delta t$ from the equation of motion $\dot{\underline{p}} = \Omega_p(\underline{b} \times \underline{p})]$ and for a subsequent period, $(\Omega_C - \Omega_p)^{-1}$, decrease $\underline{p}_1$. There is, therefore, an oscillation of $\underline{p}_1$ of amplitude $\rho_1 |db/dx| \rho_p (\Omega_C - \Omega_p)^{-1}$ with frequency $\Omega_C - \Omega_p$. Every collision time ν^{-1} the gyrophase is randomized, and this is equivalent to randomizing the phase of the $\underline{p}_1$ oscillation. Every collision time $\underline{p}_1$ makes a random step of size of the oscillation amplitude. Therefore, the diffusion coefficient of $\underline{p}_1$, D , is given by $D \sim \nu \rho_1^2 |db/dx|^2 \Omega_p^2 (\Omega_C - \Omega_p)^{-2}$. We find that the $\underline{p}$ moment of the generalized distribution $\mathcal{P}$ [1] will decay at a rate D . In the following section this rate is calculated for an arbitrary magnetic geometry using the

same type of procedure used in calculating neoclassical transport [3]. The result for arbitrary geometry is given by Eq. (46).

Quantitative Calculation

We investigate the depolarization of spin 1/2 (or Spin 1 with some generalization) particles in an arbitrary geometry. The basic assumption is that $v_{th}/a \ll \Omega_c - \Omega_p$ where Ω_c is the gyrofrequency and Ω_p is the precession frequency. The equation for the distribution function of particles is

$$\frac{\partial F}{\partial t} + \tilde{v} \cdot \frac{\partial F}{\partial \tilde{x}} + \frac{e}{m} \frac{\tilde{v} \times \tilde{B}}{c} \cdot \frac{\partial F}{\partial \tilde{v}} = C(F, F') \quad (1)$$

where $C(F, F')$ represents the Landau collision operators of the various species present. The evolution of the spin distribution function $P(t, x, v)$ is given by (See Cowley et al. [1])

$$\frac{\partial P}{\partial t} + \tilde{v} \cdot \frac{\partial P}{\partial \tilde{x}} + \frac{e}{mc} \tilde{v} \times \tilde{B} \cdot \frac{\partial P}{\partial \tilde{v}} + \Omega_p P \times \tilde{b} = C(P, F) \quad (2)$$

The parallel component of Eq. (2) can be written

$$\frac{\partial P_{\parallel}}{\partial t} + \tilde{v} \cdot \frac{\partial P_{\parallel}}{\partial \tilde{x}} + \frac{e}{mc} \tilde{v} \times \tilde{B} \cdot \frac{\partial P_{\parallel}}{\partial \tilde{v}} = C(P_{\parallel}, F) + \tilde{v} \cdot \frac{\partial \tilde{b}}{\partial \tilde{x}} \cdot P \quad (3)$$

Note that Eqs. (1) and (3) are very similar except for the term $\tilde{v} \cdot \partial \tilde{b} / \partial \tilde{x} \cdot P$, which represents the evolution of $P_{\parallel}$ due to rotation of the field in the particle frame, which couples $F_{\perp}$ to $P_{\parallel}$. The velocity moments of Eq. (1) and Eq. (3) are of interest. We are only interested in the evolution of the polarization. We wish to ignore the effects due to transport of particles and heat. However, we shall argue that the equalization of polarization over the

plasma volume takes place on a timescale $(a^2/\rho_i^2)v_{ii}$, whereas, the equalization of density takes place on a timescale $(a^2/\rho_i^2)v_{ie}$ [$v_{ie} \approx (me/mi)v_{ii}$ and a is the minor radius], so that the polarization can be taken to be uniform across the plasma volume. This is because ion-ion collisions cause transport of individual particles, but due to momentum conservation do not transport the fluid as a whole.

We define the moments of F and $P_{\parallel}$ as

$$n(\underline{x}, t) = \int F d^3 \underline{v} \quad , \quad (4)$$

$$\pi(\underline{x}, t)n(\underline{x}, t) = \int P_{\parallel} d^3 \underline{v} \quad ,$$

$$n(\underline{x}, t)g(\underline{x}, t) = \int \underline{v} F d^3 \underline{v} \quad , \quad (5)$$

$$\pi(\underline{x}, t)n(\underline{y}, t)g_{\underline{p}}(\underline{x}, t) = \int \underline{v} P_{\parallel} d^3 \underline{v} \quad ,$$

and

$$\Pi = m \int \underline{v} \underline{v} F d^3 \underline{v} \quad (6)$$

and

$$\pi(\underline{x}, t)\Pi_{\underline{p}} = \int \underline{v} \underline{v} P_{\parallel} d^3 \underline{v} \quad .$$

These quantities obey the following equations.

$$\frac{\partial n}{\partial t} + \nabla \cdot (n \mathbf{u}) = 0 \quad , \quad (7)$$

$$\frac{\partial \pi n}{\partial t} + \nabla \cdot (\pi n \mathbf{u}_p) = \int d^3 \mathbf{v} \mathbf{v} P : \frac{\partial \mathbf{b}}{\partial \mathbf{x}} \quad ,$$

$$\frac{\partial n \mathbf{u}}{\partial t} + \nabla \cdot \Pi - \frac{e}{mc} n \mathbf{u} \times \mathbf{B} = \mathbf{R} \quad ,$$

and

$$\frac{\partial n \pi \mathbf{u}_p}{\partial t} + \nabla \cdot (\Pi_p \pi) - \frac{e}{mc} \pi n \mathbf{u}_p \times \mathbf{B} = \mathbf{R}_p + \int d^3 \mathbf{v} \mathbf{v} (v P) : \frac{\partial \mathbf{b}}{\partial \mathbf{x}} \quad , \quad (8)$$

where

$$\mathbf{R} = \int d^3 \mathbf{v} \mathbf{v} C(F, F') \quad (9)$$

and

$$\mathbf{R}_p = \int d^3 \mathbf{v} \mathbf{v} C(p_{||}, F')$$

One can see that in the "equilibrium" state taking $\partial/\partial t$ of order $(p^2/a^2)v$ is consistent, so that to a good approximation [3],

$$n \mathbf{u}_\perp = \frac{1}{Q} \mathbf{b} \times (\nabla \cdot \Pi + \mathbf{R}) \quad (10)$$

and

$$n \mathbf{u}_{p\perp} = \frac{1}{Q} \mathbf{b} \times [\nabla \cdot (\Pi_p \pi) + \mathbf{R}_p + \int d^3 \mathbf{v} \mathbf{v} v P : \frac{\partial \mathbf{b}}{\partial \mathbf{x}}]$$

We make use of one important relation. Defining

$$\langle \dots \rangle \equiv \int d^3 \tilde{y} d^3 \tilde{x} (\dots) \quad (11)$$

we obtain from Eq. (3)

$$\left\langle \frac{\partial p_{\parallel}}{\partial t} \right\rangle = \langle \tilde{v} \cdot \frac{\partial \tilde{b}}{\partial \tilde{x}} \cdot \tilde{p} \rangle, \quad (12)$$

where the volume over which the $\tilde{x}$ integration takes place is such that there is no flow of particles into the volume.

The object of this calculation is to find the evolution of π . To calculate this we solve Eq. (2) order by order in the ratio of the gyroradius to the scale size. We change variables to α, μ and ϵ where

$$\tilde{v} = \tilde{v} \cdot \tilde{b} \tilde{b} + v_{\perp} (\sin \alpha \tilde{e}_1 + \cos \alpha \tilde{e}_2) \quad (13a)$$

$$\tilde{e}_1 \cdot \tilde{e}_2 = \tilde{b} \cdot \tilde{e}_1 = \tilde{b} \cdot \tilde{e}_2 = 0 \quad (13b)$$

and

$$\mu = \frac{v_{\perp}^2}{2B} \quad (14)$$

$$\epsilon = v^2 \quad (15)$$

In these coordinates $\partial \tilde{v} / \partial \alpha = \tilde{v}_{\perp} \times \tilde{b}$. We shall retain $(\tilde{v} \cdot \partial / \partial \tilde{x})_{\tilde{v}}$ but it must be remembered that the gyrophase averaging is done keeping μ and ϵ fixed. Making the strong field ordering $\Omega = \Omega_p \gg \tilde{v} \cdot \nabla$, in Eq. (2) we obtain

$$\Omega \frac{\partial \tilde{p}_0}{\partial \alpha} + \Omega \tilde{p}_0 \times \tilde{b} = 0 \quad (16)$$

and from Eq. (1)

$$\frac{\partial F}{\partial \alpha} = 0 \quad (17a)$$

Hence,

$$P_0 = P_0 b \quad (17b)$$

and

$$\frac{\partial F}{\partial \alpha} = \frac{\partial P}{\partial \alpha} = 0 \quad (17c)$$

To first order Eq. (2) becomes

$$\left\{ \frac{\partial P}{\partial t} + \tilde{v} \cdot \frac{\partial P}{\partial \tilde{x}} - C(P_0, F_0) \right\}_{\mu, \epsilon} b + P_0 \tilde{v} \cdot \frac{\partial b}{\partial \tilde{x}} = - \left\{ \Omega \frac{\partial P^1}{\partial \alpha} + \Omega P^1 \times b \right\} \quad (18)$$

We drop $\partial P_0 / \partial t$ at this order and introduce it when it is needed to find a consistent solution. P_0 is determined from the condition that we can find a periodic solution for P^1 . Dotting Eq. (18) with b and averaging over α yields

$$\oint d\alpha \left\{ \tilde{v} \cdot \frac{\partial P}{\partial \tilde{x}} - C(P_0, F_0) \right\}_{\mu, \epsilon} = 0 \quad (19)$$

Similarly, solving to this order for F_0 we obtain

$$\oint d\alpha \left\{ \tilde{v} \cdot \frac{\partial F}{\partial \tilde{x}} - C(F_0, F_0) \right\}_{\mu, \epsilon} = 0 \quad (20)$$

The solution to Eq. (20) is well known. That it is a Maxwellian is shown by

noting that

$$v_{\parallel} \frac{\partial F_0}{\partial x_{\parallel}} = b d\alpha \sim \frac{\partial F_0}{\partial x} \quad (21)$$

and by averaging over the particles parallel motion to obtain

$$\int \frac{dv_{\parallel}}{v_{\parallel}} C(F_0, F_0^1) = 0 \quad (22)$$

By the H theorem, the solution to Eq. (22) is a Maxwellian. Clearly, the Maxwellian is constant over the flux surface also. Similarly, with F_0^1 a Maxwellian, Eq. (19) shows, using a modification of the H theorem (see Cowley et al. [1], Section 4.3), that P_0 is given by

$$P_0 = \pi_0(\Psi, t) F_0(\Psi, v^2, t) \quad (23)$$

where Ψ is the flux surface coordinate.

Now consider Eq. (18) $P_{\parallel}^1$ has two parts: an α dependent particular solution to Eq. (18) and an α independent homogeneous solution which is determined in next order. The α dependent part of $P_{\parallel}^1$ is given as

$$\tilde{P}_{\parallel}^1 = \int \frac{d\alpha}{\Omega} \left(\tilde{v} \cdot \frac{\partial P_0}{\partial \tilde{x}} \right) \cdot b \quad (24)$$

Similarly, the α dependent part of F^1 is given by,

$$\tilde{F}^1 = \int \frac{d\alpha}{\Omega} \left(\tilde{v} \cdot \frac{\partial F_0}{\partial \tilde{x}} \right) \quad (25)$$

We now show that the polarization equalizes over the volume. In doing

this, rather than showing that neoclassical transport of polarization is large (the term arising from the $\nabla \cdot \prod_p \pi$ in Eq. (10)), we content ourselves with showing that classical transport of polarization, arising from R_p in Eq. (10), is large. Considering only ion-ion collisions we get

$$R_p = \int d^3v \, v \, C_{ii}(\underline{v} \times \underline{b} \cdot \frac{\partial \pi_o}{\partial \underline{x}} F_o, F_o) \quad (26)$$

Substituting this into Eq. (10) and ignoring the $\int d^3v \, v \, \underline{p} : (\partial \underline{b} / \partial \underline{x})$ term, we find

$$\frac{\partial \pi_o}{\partial t} \sim 0 \left(v_{ii} \frac{\rho^2}{a} \frac{\partial \pi_o}{\partial \underline{x}} \right) \quad (27)$$

Because we are interested in timescales long compared to this, i.e., the transport timescale

$$\frac{\partial n}{\partial t} \sim 0 \left(v_{ie} \frac{\rho^2}{a^2} n \right), \quad (28)$$

we take

$$\frac{\partial \pi_o}{\partial \Psi} \sim 0 \left(\frac{v_{ei}}{v_{ii}} \right) \frac{\pi_o}{a} \quad (29)$$

so $\pi_o = \pi_o(t)$ to the order we work. We shall show that the neoclassical part that arises from the α independent part of $P_{||}^1$ must also be of order v_{ei} if $\pi_0 = \pi_0(t)$. We solve Eq. (18) for $P_{\perp}^1$.

$$-P_o \underline{v} \cdot \frac{\partial \underline{b}}{\partial \underline{x}} = \Omega \frac{\partial P_{\perp}^1}{\partial \alpha} + \Omega_p P_{\perp}^1 \times \underline{b} \quad (30)$$

Solving this equation by differentiating with respect to α and substituting for $\partial \underline{p} / \partial \alpha$ we obtain

$$\frac{\Omega}{\Omega^2} \underline{p}_0 \cdot \underline{v} \cdot \frac{\partial \underline{b}}{\partial \underline{x}} \times \underline{b} - \underline{p}_0 \cdot \underline{v}_\perp \cdot \left(\underline{b} \times \frac{\partial \underline{b}}{\partial \underline{x}} \right) = \Omega \frac{\partial^2 \underline{p}_\perp^1}{\partial \alpha^2} + \frac{\Omega^2}{\Omega} \underline{p}_\perp^1 \quad (31)$$

There is no homogeneous solution to this equation periodic in α , so by inspection,

$$\underline{p}_\perp^1 = \frac{1}{\Omega^2} \underline{p}_0 \cdot \underline{v}_\parallel \left(\underline{b} \cdot \frac{\partial \underline{b}}{\partial \underline{x}} \times \underline{b} \right) + \frac{\Omega \underline{p}_0}{\Omega^2 \Omega^2} \left[\frac{\Omega}{\Omega^2} \underline{v}_\perp \cdot \frac{\partial \underline{b}}{\partial \underline{x}} \times \underline{b} - \underline{v}_\perp \cdot \left(\underline{b} \times \frac{\partial \underline{b}}{\partial \underline{x}} \right) \right] \quad (32)$$

Substituting $\underline{p}_\perp^1$ from Eq. (32) into Eq. (12), we find $\langle \partial \underline{p}_\parallel / \partial t \rangle$ is zero to this order since

$$\oint \underline{v} \cdot \frac{\partial \underline{b}}{\partial \underline{x}} \cdot \underline{p}_\perp^1 d\alpha = 0 \quad (33)$$

The next order in Eq. (3) yields

$$-\underline{v} \cdot \frac{\partial \underline{b}}{\partial \underline{x}} \cdot \underline{p}_\perp^1 + \underline{v} \cdot \frac{\partial \underline{p}_\parallel^1}{\partial \underline{x}} - C(\underline{p}_\parallel^1, \underline{F}_0) - C(\underline{p}_0, \underline{F}_1) = \Omega \frac{\partial \underline{p}_\parallel^2}{\partial \alpha} \quad (34)$$

Gyrophase averaging we obtain

$$\oint d\alpha \left\{ \underline{v} \cdot \frac{\partial \underline{p}_\parallel^1}{\partial \underline{x}} - C(\underline{p}_\parallel^1, \underline{F}_0) - C(\underline{p}_0, \underline{F}_1) \right\} = 0 \quad (35)$$

Because we wish to keep $\partial \underline{p}_\parallel / \partial t$ constant on a v_{ii} timescale we have set $\pi_0 = \pi_0(t)$, hence this equation becomes exactly like the F_1 equation,

$$\oint d\alpha \left[\underline{v} \cdot \frac{\partial \underline{F}_1}{\partial \underline{x}} - C(\underline{F}_1, \underline{F}_0) - C(\underline{F}_0, \underline{F}_1) \right] = 0 \quad (36)$$

with

$$P_{\parallel}^1 = \pi_0 F^1. \quad (37)$$

We see that it is consistent to take π_0 independent of $\tilde{x}$, since no $\tilde{x}$ dependence develops with time in this order.

We now solve Eq. (2) to find $P_{\perp}^2$. Let

$$K \equiv P_{\parallel}^1 \tilde{v} \cdot \frac{\partial b}{\partial \tilde{x}} + \tilde{v} \cdot \frac{\partial P_{\perp}^1}{\partial \tilde{x}} - C(P_{\perp}^1, F_0) = - \left(\Omega \frac{\partial P_{\perp}^2}{\partial \alpha} + \Omega P_{\perp}^2 \times \underline{b} \right). \quad (38)$$

We solve again by differentiating with respect to α and substituting for $\partial P_{\perp}^2 / \partial \alpha$,

$$\Omega \frac{\partial^2 P_{\perp}^2}{\partial \alpha^2} + \frac{\Omega^2}{\Omega} P_{\perp}^2 = - \frac{\partial K}{\partial \alpha} + \frac{\Omega}{\Omega} K \times \underline{b}. \quad (39)$$

To find the time evolution of $\pi_0(t)$ we substitute $P_{\perp}^2$ into Eq. (12).

Integrating by parts in Eq. (12) and using Eq. (39) we obtain,

$$\begin{aligned} \oint d\alpha \tilde{v} \cdot \frac{\partial b}{\partial \tilde{x}} \cdot P_{\perp}^2 &= \oint d\alpha \left[\tilde{v}_{\parallel} \cdot \underline{b} \cdot \frac{\partial b}{\partial \tilde{x}} \cdot P_{\perp}^2 + \frac{\Omega}{\Omega^2 - \Omega^2} \tilde{v}_{\perp} \cdot \frac{\partial b}{\partial \tilde{x}} \cdot \left(\Omega \frac{\partial^2 P_{\perp}^2}{\partial \alpha^2} + \frac{\Omega^2 P_{\perp}^2}{\Omega} \right) \right] \\ &= \oint d\alpha \left[\frac{v_{\parallel}}{\Omega} \underline{b} \cdot \frac{\partial b}{\partial \tilde{x}} \cdot K \times \underline{b} + \frac{\Omega}{\Omega^2 - \Omega^2} \tilde{v}_{\perp} \cdot \frac{\partial b}{\partial \tilde{x}} \cdot \left(- \frac{\partial K}{\partial \alpha} + \frac{\Omega}{\Omega} K \times \underline{b} \right) \right]. \quad (40) \end{aligned}$$

We consider each term in K separately. The homogeneous α independent part of $P_{\parallel}^1$ does not contribute since it gives a $P_{\perp}^2$ like $P_{\perp}^1$. The terms $\tilde{v}_{\parallel}^1$ ($\partial b / \partial \tilde{x}$) and $\tilde{v} \cdot (\partial P_{\perp}^1 / \partial \tilde{x})$ do not contribute as $\tilde{v}$ appears three times. Therefore, the gyrophase independent part is odd in $v_{\parallel}$ and disappears in the

$v_{\parallel}$ integration. This can be verified by some tedious algebra. The collision term provides the depolarization contribution. There are two contributions, Z and W .

$$-\frac{\partial \ln \pi_0}{\partial t} = \frac{1}{N} \int d^3 x (Z + W) \quad (41)$$

where

$$Z \equiv \pi_0 \int d^3 v \frac{v_{\parallel}}{\Omega_p^2} \left(\underline{b} \cdot \frac{\partial \underline{b}}{\partial \underline{x}} \right)^2 C(F_0 v_{\parallel}, F_0) \quad (42)$$

and

$$W = \pi_0 \int d^3 v' \frac{\Omega^2}{(\Omega_p^2 - \Omega'^2)^2} \{ \underline{v}_1 \cdot (\underline{b} \times \underline{v}_b) \cdot C(\frac{\Omega}{\Omega'} \underline{v}_1 \cdot (\underline{v}_b \times \underline{b}) F_0 - \underline{v}_1 \cdot (\underline{b} \times \underline{v}_b) F_0, F_0') \\ + \underline{v}_1 \cdot \underline{v}_b \cdot C(\frac{\Omega}{\Omega'} \underline{v}_1 \cdot (\underline{v}_b \times \underline{b}) \times \underline{b} F_0 - \underline{v}_1 \cdot (\underline{b} \times \underline{v}_b \times \underline{b}) F_0, F_0') \} \quad (43)$$

We make use of the identity considering ion-ion collisions only.

$$\int d^3 v \underline{v} \cdot \underline{a} \cdot C(\underline{v} \cdot \underline{b} F_0, F_0) = n_0 \left(\frac{8\sqrt{2}\pi^{1/2}}{3} \frac{n_0 \ln \Lambda e^4 z^2}{m_i v_{thi}} \right) \underline{a} \cdot \underline{b} \quad (44)$$

After some algebra we arrive at

$$-\frac{\partial \ln \pi_0}{\partial t} = -\frac{1}{N} \int d^3 x n_0 \left(\frac{8\sqrt{2}\pi^{1/2} n_0}{3} \frac{\ln \Lambda e^4 z^2}{m_i v_{thi}} \right) \rho_i^2 \left\{ \frac{\Omega^2}{\Omega_p^2} (\underline{b} \cdot \underline{v}_b)^2 \right. \\ \left. + \frac{\Omega^4}{(\Omega_p^2 - \Omega^2)^2} \left[\left(\frac{\Omega}{\Omega'} + \frac{\Omega_p}{\Omega^2} \right) \underline{v}_b \cdot \underline{v}_b + \left(1 + \frac{\Omega_p}{\Omega^2} \right) (\underline{b} \times \underline{v}_b) \cdot (\underline{b} \times \underline{v}_b) \right] \right\} \quad (45)$$

Substituting in specific field geometry and density and temperature profiles we may calculate the evolution of π_0 . The order of magnitude estimate of this is

$$\frac{\partial \ln \pi_0}{\partial t} \approx v_{ii} \frac{\rho_i^2}{L^2} \frac{\Omega^4}{(\Omega_p^2 - \Omega^2)^2}, \quad (46)$$

where L is a shear length.

We have calculated the depolarization in an arbitrary geometry. The formula is given in Eq. (45) where π_0 is the mean value of $P \cdot b$.

The result is in agreement with that for a slab equilibrium given in Ref. [1]. The depolarization rate Eq. (46) is only marginally faster than the flattening of the polarization which goes at the rate $v_{ii} \rho_i^2 / a^2$ [with neoclassical effects this would be enhanced by $(R/a)^2$]. The lifetime of the plasma is typically much shorter than the depolarization time given by Eq. (46), since the anomalous losses are much larger than these classical collisional losses.

ACKNOWLEDGMENTS

We are grateful for a number of discussions with E. J. Valeo and a stimulating discussion with S. Tamor.

This work supported by DoE Contract No. DE-AC02-76-CHO-3073.

REFERENCES

1. S. C. Cowley, R. M. Kulsrud and E. J. Valeo, Princeton Plasma Physics Laboratory Report PPPL-2119 (1984), submitted to Physics of Fluids.
2. S. Tamor, Bull. Am. Phys. Soc. 29 (1984) 2S23.
3. F. L. Hinton and R. Hazeltine, Rev. Mod. Phys. 48 (1976) 230.

EXTERNAL DISTRIBUTION IN ADDITION TO UC-20

Plasma Res Lab, Austr. Nat'l Univ, AUSTRALIA
 Dr. Frank J. Paoloni, Univ of Wollongong, AUSTRALIA
 Prof. I.R. Jones, Flinders Univ., AUSTRALIA
 Prof. M.H. Brennan, Univ Sydney, AUSTRALIA
 Prof. F. Cap, Inst Theo Phys, AUSTRIA
 Prof. Frank Verheest, Inst theoretische, BELGIUM
 Dr. D. Palumbo, Dg XII Fusion Prog, BELGIUM
 Ecole Royale Militaire, Lab de Phys Plasmas, BELGIUM
 Dr. P.M. Sakanaka, Univ Estadual, BRAZIL
 Dr. C.R. James, Univ of Alberta, CANADA
 Prof. J. Teichmann, Univ of Montreal, CANADA
 Dr. H.M. Skarsgard, Univ of Saskatchewan, CANADA
 Prof. S.R. Sreenivasan, University of Calgary, CANADA
 Prof. Tudor W. Johnston, INRS-Energie, CANADA
 Dr. Hannes Barnard, Univ British Columbia, CANADA
 Dr. M.P. Bachynski, MFB Technologies, Inc., CANADA
 Chalk River, Nucl Lab, CANADA
 Zhengou Li, SW Inst Physics, CHINA
 Library, Tsing Hua University, CHINA
 Librarian, Institute of Physics, CHINA
 Inst Plasma Phys, Academia Sinica, CHINA
 Dr. Peter Lukac, Komenského Univ, CZECHOSLOVAKIA
 The Librarian, Culham Laboratory, ENGLAND
 Prof. Schatzman, Observatoire de Nice, FRANCE
 J. Radet, CEN-CE6, FRANCE
 AM Dupas Library, AM Dupas Library, FRANCE
 Dr. Tom Mui, Academy Bibliographic, HONG KONG
 Preprint Library, Cent Res Inst Phys, HUNGARY
 Dr. S.K. Trehan, Panjab University, INDIA
 Dr. Indra Mohan Lal Das, Banaras Hindu Univ, INDIA
 Dr. L.K. Chawla, South Gujarat Univ, INDIA
 Dr. R.K. Chhajlani, Vikram Univ, INDIA
 Dr. B. Dasgupta, Saha Inst, INDIA
 Dr. P. Kaw, Physical Research Lab, INDIA
 Dr. Phillip Rosenau, Israel Inst Tech, ISRAEL
 Prof. S. Cuperman, Tel Aviv University, ISRAEL
 Prof. G. Rostagni, Univ Di Padova, ITALY
 Librarian, Int'l Ctr Theo Phys, ITALY
 Miss Clelia De Palo, Assoc EURATOM-ENEA, ITALY
 Biblioteca, del CNE EURATOM, ITALY
 Dr. H. Yamato, Toshiba Res & Dev, JAPAN
 Direc. Dept. Lg. Tokamak Dev. JAERI, JAPAN
 Prof. Nobuyuki Inoue, University of Tokyo, JAPAN
 Research Info Center, Nagoya University, JAPAN
 Prof. Kyoji Nishikawa, Univ of Hiroshima, JAPAN
 Prof. Sigeru Mori, JAERI, JAPAN
 Library, Kyoto University, JAPAN
 Prof. Ichiro Kawakami, Nihon Univ, JAPAN
 Prof. Satoshi Itoh, Kyushu University, JAPAN
 Dr. D.I. Choi, Adv. Inst Sci & Tech, KOREA
 Tech Info Division, KAERI, KOREA
 Bibliotheek, Pom-Inst Voor Plasma, NETHERLANDS
 Prof. B.S. Liley, University of Waikato, NEW ZEALAND
 Prof. J.A.C. Cabral, Inst Superior Tecn, PORTUGAL
 Dr. Octavian Petrus, ALI OJZA University, ROMANIA
 Prof. M.A. Hellberg, University of Natal, SO AFRICA
 Dr. Johan de Villiers, Plasma Physics, Nucor, SO AFRICA
 Fusica Div. Library, JEN, SPAIN
 Prof. Hans Wilhelmson, Chalmers Univ Tech, SWEDEN
 Dr. Lennart Stenflo, University of UMEA, SWEDEN
 Library, Royal Inst Tech, SWEDEN
 Centre de Recherches, Ecole Polytech Fed, SWITZERLAND
 Dr. V.T. Tolok, Kharkov Phys Tech Ins, USSR
 Dr. D.D. Ryutov, Siberian Acad Sci, USSR
 Dr. G.A. Eliseev, Kurchatov Institute, USSR
 Dr. V.A. Glukhikh, Inst Electro-Physical, USSR
 Institute Gen. Physics, USSR
 Prof. T.J.M. Boyd, Univ College N Wales, WALES
 Dr. K. Schindler, Ruhr Universitat, W. GERMANY
 Nuclear Res Estab, Julich Ltd, W. GERMANY
 Librarian, Max-Planck Institut, W. GERMANY
 Bibliothek, Inst Plasmaforschung, W. GERMANY
 Prof. R.K. Janev, Inst Phys, YUGOSLAVIA