✓
MARCH 1978

PPPL-1439
UC-20f

THE EFFECT OF NEUTRAL PARTICLES
ON ANOMALOUS SKIN CURRENT
IN TOKAMAKS

BY

MASTER

M. L. STOENESCU AND T. M. SMITH

**PLASMA PHYSICS
LABORATORY**

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

**PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY**

This work was supported by the U. S. Department of Energy Contract No. EY-76-C-02-3073. Reproduction, translation, publication, use and disposal, in whole or in part, by or for the United States Government is permitted.

THE EFFECT OF NEUTRAL PARTICLES ON
ANOMALOUS DEIN CURRENT IN TUFAMAP

by

M. L. Moenonen and T. M. Smith

Princeton University, Plasma Physics Laboratory
Princeton, New Jersey 08540

PLPL 1439

April 1973

Abstract

The effect of neutral particles on the anomalous
dein current in TUFAMAP is studied.

This work was supported by the U. S. Department of Energy Contract No.
E(11-1) 2735.

The Effect of Neutral Particles
on Anomalous Skin Current in Tokamaks

by

M. L. Stoenescu and T. M. Smith

Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08540

ABSTRACT

The anomalously rapid skin current relaxation observed in some experiments may be explained by any mechanism which cools the electrons thus increases the resistivity and limits the current increase in the plasma boundary, such as enhanced ion conduction, loss of high energy tail electrons or influx of cold neutrals. The current penetration into the plasma and the evolution of the electron temperature from hollow to central peaked radial profile are evaluated for a PLT (Princeton Large Torus) experiment and indicate the significant influence of the neutrals on radial gradients and thus on the conditions favouring unstable regimes. One observes the skin current relaxation in the presence of neutrals in contrast with the skin current persistence in the absence of neutrals.

1. INTRODUCTION

The time evolution of a tokamak plasma discharge has been modeled extensively. Some examples are presented in / 1 / - / 3 / . Basically all present models are equivalent, describing the magnetic field (or the electric current) diffusion into the plasma and the radial particle and energy transport in the poloidal plane. Two dimensional aspects of the poloidal transport are taken into account, for parameters which do not vary considerably over a magnetic surface, by developing a magnetic flux coordinate system of reference and deriving the shape of the magnetic surfaces.

The differences encountered in various time dependent predictions originate from variations in the transport models used, as the theory on transport in tokamak operation conditions is in an evolutive phase.

Numerical predictions also vary according to the type of species assumed to play a determinant role. Some impurities and the background plasma neutrals are often neglected in order to reduce the computational volume.

An important impact on the numerical evaluations is produced by the assumptions made on plasma boundary conditions, which are somewhat arbitrary in view of the experimental errors in boundary plasma description.

Turbulent flows and microinstabilities add to the complexity of theoretical modeling and theories incorporating their effect are presently considered / 4 / .

The results presented in this paper are based on a model described in / 5 / which characterizes a plasma evolving quasistatically

in a variable magnetic field. Diffusion and conduction coefficients are introduced in accordance with / 1 / and their values differ with the functional regime of the plasma. Convective transport is permitted in addition to the diffusive transport, as results from the conservation equations in / 5 / .

2. THEORY

The computer model described in / 5 / can be summarized as follows.

The plasma is subdivided into toroidal shells by a set of closed concentric surfaces $\overline{r}_i$, as shown in poloidal cross section in Figure 1. The plasma magnetic field and electric current are tangent to these surfaces and the particle pressure is constant on each surface.

The following parameters control the plasma flowing between two surfaces: inductive electric fields generated by the ohmic heating coils, shaping field coils, and the electric currents of all other plasma shells, collisions between various participating species, viscous forces and particle sources (injection, annihilation, and convection). An Ohm's law describes the toroidal plasma current in each shell according to equation (1) (Appendix) .

The surfaces are permeable to particle and energy transfer between plasma shells and across the overall plasma boundary.

The particle and energy balance in each plasma shell are described by equations (2) - (4), taking into account, as indicated, collisions, radiation, ohmic heating, diffusion and conduction, where injection, fusion, and compression are omitted for the present evaluation.

The plasma stabilization in the magnetic field is described by an equilibrium equation (5) (based on momentum conservation), which relates at every moment the plasma current, location (major radius) and size (minor radius), to the momentary magnetic field.

The validity of the model is based upon the assumption that the magnetic surfaces have a continuous structure in time, and that the

plasma is in quasistatic equilibrium with the magnetic field.

In the present model the toroidal magnetic field of the poloidal plasma current is neglected; this approximation is considered acceptable, taking into account the little effect that a correction to the toroidal field would have.

3. SKIN CURRENT FORMATION AND CURRENT PENETRATION INTO THE PLASMA

For each applied voltage and resistive voltage drop, the toroidal plasma current time rate of change in the j th plasma shell, $\dot{I}_j$, increases with the radius according to Kirchoff's law (equation (1)) :

$$M_{jj} \dot{I}_j + \sum_{j' = j} M_{j'j} \dot{I}_{j'} = U_j - I_j R_j \quad (7)$$

where $M_{j'j}$ represents the mutual inductance coefficients between the plasma sections j' and j , U_j is the voltage resulting from coil - plasma inductive coupling and

$$I_j R_j = J_j^2 \pi R_o \eta \quad (8)$$

represents the ohmic voltage drop in the j th plasma shell. J_j is the plasma current density, R_o is the major radius of the torus, and η is the resistivity parallel to the magnetic field generated by electron - ion and electron - neutral collisions:

$$\eta = \eta_{ei} + \eta_{en} \quad (9)$$

The electron - ion resistivity is estimated by Spitzer / 6 / :

$$\eta_{ei} = 3.8 \times 10^3 \kappa_z \ln \Lambda T_e^{-3/2} \quad \text{Ohm cm} \quad (10)$$

where

$$\begin{aligned}\gamma_2 &= 0.582 \quad \text{for } Z = 1 \\ &= 0.683 \quad \text{for } Z = 2 \\ &= 1.0 \quad \text{for } Z = \infty\end{aligned}$$

and T_e is in Kelvin degrees. The electron - neutral resistivity results directly from the collisional momentum transfer:

$$\eta_{en} = \left(4 m_e / 3 n_e e^2 \right) n_n \left(8 k T_e / \pi m_e \right)^{1/2} \times \int e^{-\xi^2} \xi^5 Q_{en} \left(\left(2 k T_e / m_e \right)^{1/2} \xi \right) d\xi \quad (11)$$

The solution of equation (7) may be expressed as a linear combination of the differences $U_j - I_j R_j$ as follows:

$$\dot{I}_j = \sum_{j'} C_{jj'}^j (U - I_{j'} R_{j'}) \quad (12)$$

where the externally induced voltage $U_{j'}$ is taken to be the same for all plasma shells. The elements of the matrix $C_{jj'}^j$, depend only upon inductance coefficients. The radial distribution of the time rate of change of the plasma current density therefore depends upon the geometric characteristics of the tokamak through the matrix $C_{jj'}^j$, and upon the plasma state through the plasma current density and resistivity. It is obvious that, subject to the radial profiles of $I_j R_j$, the plasma current time rate of change may enhance either a skin current or a centrally peaked current. In particular, for a uniform plasma,

the radial profile of $\dot{I}_j$ is uniquely determined by geometric effects:

$$\dot{I}_j = (U - IR) \sum_{j'} C_{jj'}^j \quad (13)$$

The parameter which mostly influences the plasma resistance is the electron temperature T_e , according to expression (10). It follows that equation (12) and the electron energy conservation equation (4) determine the coupling between the plasma current density profiles and the electron temperature profiles as summarized below:

$$T_e \xrightarrow{(10)} R \xrightarrow{(12)} \dot{I} \xrightarrow{\text{delay}} I \xrightarrow{(4)} \dot{T}_e \xrightarrow{\text{delay}} T_e$$

In plasma regions where the electron temperature is highest, the resistance is lowest, the rate of increase of plasma current density is highest and the plasma current density increases rapidly. This ohmically heats the electrons, speeding the plasma current increase. It is thus likely that the plasma current density radial profiles and electron temperature profiles are qualitatively similar. However, this is true for applied voltages considerably larger than the ohmic voltage drop, in which case the plasma current density varies rapidly in time.

During the initial phase of a tokamak start-up for which the $I R$ profile is almost independent of radius the plasma current increases most rapidly at the plasma edge, according to equation (13). This "skin current" causes a more pronounced ohmic heating of electrons near the plasma edge. If this ohmic heating is not overwhelmed by conductive and collisional cooling, the ohmic voltage drop at the plasma

edge remains small due to the dependence of resistivity upon electron temperature, and the skin current, produced by inductive effects, is sustained. If, on the other hand, ohmic heating at the edge is overcome by cooling effects, then the ohmic voltage drop at the edge rises rapidly with the current, the current increase at the edge is hindered, and the current increase in the plasma interior is enhanced by inductive effects within the plasma. Thus the radial peak of the plasma current migrates toward the plasma interior, and the radial peak of electron temperature follows, if ohmic heating dominates the time rate of change of electron temperature in the plasma interior. The rate of this migration is determined by the relative values of externally applied voltage and ohmic voltage drop within the plasma.

The above considerations are presented in order to support the following observations. The coefficients C_j^j , in equation (12) depend only on the geometry of the tokamak; therefore, for each reactor there is a different radial $I_j R_j \propto J_j \eta_j$ profile which defines the transition between skin current enhancement and skin current relaxation conditions. Given an experimentally observed plasma current density time variation, one may solve equation (12) for the resistivity time variation. According to relation (14) there is a delay in the temporal coupling between $\dot{J}(x)$ and $\dot{T}_e(x)$ and therefore the radial maxima of the plasma current density J and the electron temperature T_e are not in phase.

4. RESULTS

The results presented in 2 - 16 describe the skin current formation in a PLT discharge and the influence of neutrals present near the plasma edge on the current penetration into the plasma.

Figure 2 represents the shaping field coil currents versus time and Figure 3 represents a typical PLT ohmic heating coil current.

Figures 4 - 13 describe a PLT start-up with an assumed neutral particle density radial profile. The plasma current density time rate of change predicted by equation (12) is graphed on Figure 4. The radial profile at time $t=0$ graphed on Figure 4b indicates the contribution of geometry to the skin current formation as expressed in equation (13), since $U - IR$ is independent of radius at $t=0$ in the present example. U represents the total applied voltage of the external coils (shaping and ohmic heating). Figure 5 shows the time variation of $U - IR$ which contributes to the curves on Figure 4. The plasma current density time evolution in Figure 6 results from the time rate of change indicated on Figure 4. The plasma current density, peaked initially in the outer shell (skin type current), progresses gradually towards a centrally peaked current, and the diffusion rate radial maximum of the plasma current density can be evaluated from Figure 6b. The total plasma current consistent with Figure 6 is represented on Figure 7. The electron temperature time rate of change is represented on Figure 8 and is a result of ohmic heating, and of electron cooling through collisions and conduction. The resulting electron temperature time dependence is shown on Figure 9, and one can see the reversal of the radial profile from one peaked at the edge to one peaked at the center. The ions as a whole species are heated by electron-ion collisions only, yet a radial redistribution of their enthal-

py due to conductive-diffusive transport takes place. The ion temperature time rate of change and the ion temperature are represented on Figures 10 and 11. Because of the relatively slow rise time of the PLT compared to previous generation tokamaks, the electrons and ions are quite well coupled thermally. The electron and ion heat fluxes associated with the above conditions are shown on Figures 12 and 13 respectively.

Figures 14-16 represent the plasma current density, electron temperature which result from a numerical evaluation similar with the one above with the exception of the neutral density which is zero. Comparison of Figures 14-16 with Figures 6,9 and 11 respectively indicates a more sustained skin current and hollow electron temperature profile in the absence of neutrals.

5. CONCLUSIONS

The skin current time evolution and the current penetration into the plasma are determined by geometric effects represented in the mutual inductive coupling of a plasma shell with other plasma shells and with the magnetic coils, and by collisional effects represented by the resistive properties of the plasma.

It is shown that the presence of neutral particles in the plasma outer region may account for anomalously rapid penetration of the current into the plasma through an increase in resistivity due to electron cooling resulting from elastic and inelastic (excitation and ionization) collisions with the neutrals. The electron cooling increases the electron - ion resistivity. The electron - neutral resistivity is smaller than the electron - ion resistivity as long as the neutral density remains below the ion density value.

The neutrals present in the plasma outer shells may be generated in several ways: through local recombination, which is unlikely above a certain temperature, through diffusion from the scrape-off, through back-scatter of the ions neutralised at the limiter surface and as a result of turbulent mixing in the high gradient conditions of the plasma edge. The neutrals which have penetrated into the plasma become excited and ionized, cooling the electrons and reducing the ionization rate. A nonzero balance of neutral particle influx and ionization rate accounts for the presence of neutral particles in the plasma outer regions.

There is experimental evidence of the neutrals in the line radiation of the background plasma excited states. Additional

experimental data would be valuable due to the difficulties in theoretical estimates of neutral particle transport in turbulent mixing conditions.

Previous studies of skin effect were reported in the literature / 7 / - / 13 / . Duchs, Furth, and Rutherford / 7 / have shown that the suppression of the skin effect which is suspected to take place in some experiments may be explained either by an enhancement of the plasma resistivity or thermal conductivity. The latter effect would, however, lead to unacceptably high heat transfer to the limiters of large tokamaks. McBride et al. / 8 / review the current penetration conditions in tokamaks of various sizes and indicate the distinction between regimes characterized by slow rise-time and high density, in which electron and ion temperatures remain closely coupled throughout the current rise so that ion heat conduction may relax the skin current, and regimes characterized by fast rise-time and low density, where electrons and ions thermally decouple and the ohmic heating leads to skin current formation. The current-driven ion acoustic instability and the low-frequency electron temperature gradient instability are the micro-instabilities which may influence transport during skin current formation, although these are not likely to occur. It is suggested that MHD modes, in particular the resistive tearing modes, must be invoked when classical toroidal transport processes fail to explain the anomalous skin current annihilation. Furth, Rutherford, and Selberg / 9 / indicate that when a local minimum of the safety factor occurs within the plasma, resistive modes become unstable. Hutchinson and Morton / 10 / have shown experimentally that conditions for a resistive MHD instability of $m = 4$, $n = 1$ exist in the early stage of the LT-3 tokamak startup. Abundant electron runaway / 11 / is characteristic

of the disrupted magnetic surfaces associated with the unstable resistive mode. Consequently, the hollow current profiles which develop initially relax to approximately uniform distributions.

The skin current generation during the mostly ionized stage cannot be explained independently of the electrical breakdown stage (/ 13 / , / 14 /) during which hollow current profiles are observed.

In conclusion, the rapid relaxation of the skin current cannot be explained by classical ion heat transport. Resistive tearing modes are likely to develop, particularly in early stages, but may not be entirely responsible for the observed plasma time evolution in the present largest tokamaks. The effect of the neutral particles in the plasma outer region on the skin current relaxation time is evaluated in the present paper and it is shown that the neutral particle effect on the plasma resistivity (through collisional cooling of electrons) may be responsible for the rapid current penetration.

The above observations concerning the causes of skin current relaxation are by no means exhaustive. As any factor which influences the resistivity affects the electric current, theories on anomalous resistivity / 4 / as well as theories on enhanced collisional electron cooling (present paper) or radiative impurity cooling (paper to be published) are justly related to the skin current anomaly. Systematic experimental data on electron temperature, ion temperature, radiation (from neutrals and impurities), plasma current, and coil current time evolution during pre-beam heating is highly desirable.

APPENDIX

Mathematical Formulation

$$\begin{aligned} L_{jj} \dot{i}_j &= - M_{cj} \dot{i}_c - \sum_{\xi} M_{\xi j} \dot{i}_{\xi} \\ &- \sum_{j' \neq j} M_{j'j} \dot{i}_{j'} - R_j I_j \end{aligned} \quad (1)$$

$$\frac{\partial n_i}{\partial t} = \text{div} (- D \text{grad } n_i) + S_i \quad (2)$$

$$\begin{aligned} \frac{\partial}{\partial t} (\frac{3}{2} n_i T_i) &= \text{div} (K_i \text{grad } T_i + \frac{3}{2} T_i D \text{grad } n_i) \\ &- C_1 \frac{ (\frac{3}{2} n_i T_i) n_e }{ T_e^{3/2} } (1 - \frac{T_e}{T_i}) \end{aligned} \quad (3)$$

$$\begin{aligned} \frac{\partial}{\partial t} (\frac{3}{2} n_e T_e) &= \text{div} (K_e \text{grad } T_e + \frac{3}{2} T_e D_1 \text{grad } n_e) \\ &+ C_1 \frac{ (\frac{3}{2} n_i T_i) n_e }{ T_e^{3/2} } (1 - \frac{T_e}{T_i}) \\ &+ \gamma J^2 - \frac{3}{2} \nu_{en} (n_e T_e - n_n T_n) \\ &- W_{\text{Brem}} - W_{\text{cycl}} \end{aligned} \quad (4)$$

$$B_{eq} = - 10^{-7} \frac{I_p}{R_p} (\ln (\frac{8 R_p}{a_p}) - \frac{5}{4} + \beta_{\theta}) \quad (5)$$

ACKNOWLEDGEMENTS

Are addressed to S. Yoshikawa for helpful discussions and for suggesting the present publication.

This work was supported by the U. S. Department of Energy Princeton University Plasma Physics Laboratory Contract No. EY-76-C-02-3073 and the S.R.S.A. Contract No. E(11-1)-2735.

REFERENCES

- / 1 / Rutherford, P. H., Duchs, D. F., Princeton Plasma
 Physics Lab., Princeton Univ., MATT-1272 (1976)
- / 2 / Hogan, J. T., Dory, R. A., Controlled Fusion and
 Plasma Physics 2 (1972) 233
- / 3 / Conn, R. W., Kesner, J., Nuclear Fusion 15 (1975) 775
- / 4 / Lin, A. T., Dawson, J. M., Phys. Fluids 21 (1978) 109
- / 5 / Stoenescu, M. L., Smith, T. M., Smith, D. E.,
 A Computer Model for the Time Evolution of Toroidal
 Plasmas (to be published)
- / 6 / Spitzer, L., Harm, R., Phys. Rev. 89 (1953) 977
- / 7 / Duchs, D. F., Furth, H. P., Rutherford, P. H.,
 Nuclear Fusion 12 (1972) 341
- / 8 / McBride, J. B., Klein, H. H., Byrne, R. N.,
 Krall, N. A., Nuclear Fusion 15 (1975) 393
- / 9 / Furth, H. P., Rutherford, P. H., Selberg, H.,
 Phys. Fluids 16 (1973) 1054
- / 10 / Hutchinson, I. H., Morton, A. H., Nuclear Fusion
 16 (1976) 447
- / 11 / Hutchinson, I. H., Strachan, J. D., Nuclear Fusion
 14 (1974) 649
- / 12 / Abramov, V. A., Vikhrev, V. V., Pogutse, O. P.,
 Sov. J. Plasma Phys. 3 (1977) 288
- / 13 / Strachan, J. D., Nuclear Fusion 16 (1976) 433

Figure 1

Shaping field coil currents (A)

Figure 2

Figure 3

Figure 4 a

Figure 4 b

Figure 5

Figure 6 a

Figure 6 b

Figure 7

Figure 8 a

Figure 8 b

Figure 9 a

Figure 9 b

Figure 10 a

Figure 10 b

Figure 11 a

Figure 11 b

Figure 13

Figure 14 a

Figure 14 b

Figure 15 a

Figure 15 b

Figure 11.1