Calculation of Magnetic Field Ripple Effects in Circular and Noncircular Tokamaks

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CALCULATION OF MAGNETIC FIELD RIPPLE EFFECTS IN CIRCULAR AND NONCIRCULAR TOKAMAKS

N. A. Uckan¹

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ABSTRACT

A computer model (RIPPLE) was developed to examine the magnetic field ripple effects on plasma transport and on scaling in circular and noncircular tokamaks. Calculations include the radial and poloidal variation in the magnitude of the field ripple. Two main magnetic field computer programs were used to calculate the magnetic field due to current flowing in a coil of finite rectangular cross section: BFULT for tori of circular coils, and BOVAL for tori of noncircular coils. This paper presents the relevant results and discusses the criteria for the choice of the number of toroidal field coils for a given tokamak configuration.

I. INTRODUCTION

In the design of tokamaks, the choice of the number of toroidal field (TF) coils depends on the toroidal field ripple that can be tolerated by plasma physics considerations^{1,2} and on the need for access space. Increasing the number of TF coils reduces the field ripple but makes access more difficult. Increasing the number of coils also, of course, involves increased costs. The number of TF coils necessary in any tokamak device needs to be analyzed from the standpoint of maximum tolerable ripple. Evaluation criteria must include²: (1) plasma energy transport, (2) the loss of fast ions, i.e., injected particles and/or

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alpha particles, and (3) the relaxation of toroidal flows induced in the plasma.

In order to reduce field ripple, the number of TF coils can be increased, the horizontal TF coil bore can be extended, or the shape of the TF coils can be changed. However, as mentioned earlier, increasing the number of TF coils seriously restricts the design of the mechanical support system for the blanket and shield and makes access more difficult. Trade-offs among these alternatives can be studied to optimize the design.

A computer model (RIPPLE) for ripple analysis has been developed to study the magnetic field ripple effects on plasma transport and scaling in circular and noncircular tokamaks. This model includes comparison with various energy transport scaling laws such as neoclassical transport, trapped particle instabilities, and empirical scaling. Calculations include both radial and poloidal variations in the magnitude of the field ripple. The Whitson, van Rij, and Clark³ magnetic field code has been adapted to calculate magnetic field due to current flowing in a coil of rectangular cross section. The coil lies in a plane and make take any shape except one where a multivalued function is necessary to describe the path of the current.

Section II summarizes the plasma physics considerations; Sect. III outlines the Program Summary; Sect. IV presents the numerical results for given circular and noncircular tokamak configurations; Sect. V discusses criteria involved in the evaluation of tolerable field ripple and presents conclusions.

II. PLASMA PHYSICS CONSIDERATIONS

A critical element in the design and interpretation of tokamak experiments is the magnetic field structure, which includes the poloidal and toroidal magnetic field systems in both their ideal and realistic forms. In the present work we consider the toroidal magnetic field system only.

The non-axisymmetric toroidal magnetic field ripple caused by the discrete coils can form an additional trap for particles, loss regions, and plasma transport. Then the major question that arises is the maximum toroidal field ripple that can be tolerated from plasma physics considerations. In this section we summarize the effects of toroidal field ripple on: (1) the plasma transport coefficients, (2) the loss of fast ions, and (3) the relaxation of toroidal flows induced by neutral beam injection.

Considering a simple model of tokamak confinement geometry, the resulting magnetic field can be written as

$$\underline{B} = \frac{B_0}{h} \left[\frac{B_r}{B_\phi}, \theta, 1 - \delta(r, \theta) \cos N\phi \right], \quad (1)$$

where r and θ are polar coordinates in the minor cross section of the torus and ϕ is the angular coordinate along the magnetic axis; $h = 1 + (r/R_0) \cos \theta = 1 + \epsilon \cos \theta$; $\delta(r, \theta) = (B_{\max} - B_{\min}) / (B_{\max} + B_{\min}) \ll r/R_0$ is the depth of the ripples and can approximately be modeled to be¹ $\delta \sim \delta(r) g(\theta) \sim (r/a)^m \exp(-\beta\theta^2)$; N is the number of TF coils; and $\theta = B_\theta/B_\phi$ is the ratio of poloidal to toroidal field. Ignoring the terms of order δ^2 , the field strength is approximately

$$B \simeq B_0 [1 - \epsilon \cos \theta + \frac{1}{2}(\frac{\epsilon}{q})^2 + \frac{\epsilon A}{2} \cos^2 \theta - \delta(r, \theta) \cos N\phi], \quad (2)$$

where

$$A = \frac{\epsilon}{2} (\sigma^2 - 1), \quad (3)$$

with σ being elongation of the plasma cross section in vertical direction (see Fig. 1) and q being the safety factor. Following Ref. 1, we find the effective ripple well depth along the field line to be

$$\begin{aligned} \Delta(r, \theta; \sigma) &= \frac{B_{\max} - B_{\min}}{B_0} \\ &= 2\delta(r, \theta) \left(\sqrt{1 - \alpha^2(r, \theta) \sin^2 \theta (1 - A \cos \theta)^2 -} \right. \\ &\quad \left. \alpha(r, \theta) |\sin \theta (1 - A \cos \theta)| \left\{ \frac{\pi}{2} - \sin^{-1} [\alpha(r, \theta) |\sin \theta (1 - A \cos \theta)|] \right\} \right), \end{aligned} \quad (4)$$

where $\alpha(r, \theta) = \epsilon/Nq\delta(r, \theta) = \epsilon/Nq\delta(r) q(\theta) = \alpha(r)/g(\theta)$.

The expression for the ion heat conductivity coefficient for ripple trapping is^{1,4}

$$\chi_i^\delta \simeq 46.5 \frac{\delta(r)^{3/2}}{v_{ei}} \frac{G(\alpha, \beta; \sigma)}{(\frac{m_i}{m_e})^{1/2}} \left(\frac{cT_i}{eB_0 R_0 \sigma} \right)^2, \quad (5)$$

and for banana drift is^{1,5}

$$\chi_i^{BD} \simeq 9.23 \epsilon^{3/2} \delta^2(r) \frac{N^2}{(m+2)^2} \frac{q^2 Q^2}{v_{ei}} \left(\frac{m_i}{m_e} \right)^{1/2} \left(\frac{cT_i}{eB_0 R_0 U} \right)^2, \quad (6)$$

where $Q = d \ln q / d \ln r$ and

$$\begin{aligned} G(\alpha, \beta; \sigma) &= \frac{1}{\pi} \int \left[\frac{\Delta(r, \theta; \sigma)}{2\delta(r)} \right]^{3/2} \sin^2 \theta (1 - A \cos \theta)^2 d\theta \\ &= \frac{2}{\pi} \int_c d\theta \sin^2 \theta (1 - A \cos \theta)^2 [g(\theta)] \quad x_{(\text{cont'd next page})} \end{aligned}$$

$$x \left(1 - \alpha^2(r) \sin^2 \theta (1 - A \cos \theta)^2 / g^2(\theta) - \frac{\alpha(r)}{g(\theta)} |\sin \theta (1 - A \cos \theta)| \right. \\ \left. x \left\{ \frac{\pi}{2} - \sin^{-1} \left[\frac{\alpha(r)}{g(\theta)} |\sin \theta (1 - A \cos \theta)| \right] \right\} \right)^{3/2}, \quad (7)$$

with $\int_c = \int_0^{\theta_1} + \int_{\theta_2}^{\pi}$, where θ_1 and θ_2 are the roots of

$$1 - \alpha^2(r) \sin^2 \theta (1 - A \cos \theta)^2 / g^2(\theta) = 0. \quad (8)$$

It will be shown in Sect. IV that the poloidal angle variation in the field ripple strength reduces the quantity $G(\alpha, \beta; \sigma)$, depending on TF coil and on plasma shape as well as on the plasma location in the coil by a significant amount in comparison with the results of $\beta = 0$ cases.

It is well known that deviations from axisymmetry in toroidal devices lead to the formation of loss regions that are related to the fact that particles trapped in the ripple mirrors tend to be localized and, therefore, are subject to an uncompensated ∇B drift motion. For the background plasma, collisions are usually strong enough to scatter the particles out of the ripple-trapping region in velocity space before they drift out of the plasma. At the higher ion energies typical of neutral beam injection into large devices (> 100 keV) or alpha particles produced from D-T fusion (3.5 MeV), collisional effects are much weaker and the fast ions trapped in the ripples can drift out of the plasma before collisional detrapping occurs. The loss for particles diffusing into the ripple loss region has been estimated analytically.⁶ The detail of calculation on fast ion losses will appear in a subsequent publication. The calculations show that most of the alpha particles can be lost during

the slowing down process; however, loss occurs primarily in energies on the order of or below 200 – 300 keV, so it appears that they deposit their energy before they escape from the system.

In general, magnetic field ripple has the beneficial effect of producing a viscous drag on toroidal rotations or flows in the plasma, such as may be introduced by neutral beam injection and/or alpha particle losses. (See Ref. 2 for more detail.)

III. PROGRAM SUMMARY

In order to use the routine, one must provide a description of the shape of the coil and of the plasma shape and location in the coil. The present version assumes a problem symmetric about the R axis ($\theta = 0$). (See Fig. 1.) A description of the coil can be obtained separately from another computer routine where the coil shaping has been specified by stability and minimum stress considerations.⁷

Two main magnetic field computer programs have been used to calculate toroidal field ripple: BFULT for tori of circular coils, and BOVAL for tori of noncircular coils.³

BFULT: BFULT calculates fields generated by tori of circular coils with rectangular cross section. Gaussian integration is used to integrate the fields produced by cylindrical current sheets across the radial depth of each coil. An elliptic integral formulation is used to calculate cylindrical current sheet fields.⁸ A version of BFULT has been specifically set up for calculating magnetic field ripple across a grid of points within the bore of the torus. The inputs required for BFULT are: coil dimensions, current density, number of coils, torus dimensions, and

information for specifying the grid of points where ripples are to be calculated.

BOVAL: BOVAL can calculate fields generated by a torus of coils with rectangular cross section and most any profile.³ The field produced by a short rectangular wedge-shaped piece of the coil with some radius of curvature can be expressed analytically; this expression is then numerically integrated around the coil profile to give the field produced by the entire coil. The profile of the coil can be specified in a number of different ways. Two methods that have been used for calculating ripple are: specifications of a number of points (typically about 30) along the inner bore of the coil, fitting a harmonic series to those points to provide an analytic expression for the coil shape; storing in a table a large number of points describing the coil shape. Besides the coil shape specifications information, other inputs to this program are similar to those required for BFULT.

RIPPLE was developed to study the magnetic field ripple effects on plasma transport and scaling in circular and/or noncircular tokamaks. This model consists of a set of various heat transport coefficients including neoclassical transport, trapped particle instabilities, empirical scalings, and enhanced heat transport due to ripple trapping.¹⁻² (See Appendix A.)

RIPPLE: This program calculates the ion heat conduction losses for circular and noncircular plasmas. The input parameters required for this program are:

1. DATA,RPL/RMAJOR, RMINOR, BMAG, NCOIL, DENØ, PDEN, TEMPØ, STEMP, QIEDGE, BETAR, MRPPL, ZEF, SIGMA, DEL, IMAX, RMAX, CURR.

Descriptions of Parameters:

RMAJOR — Major radius (cm)
 RMINOR — Minor plasma radius (cm)
 BMAG — Magnetic field on axis (kG)
 NCOIL — Number of TF coils (= N)
 DENØ — Average particle density on axis ($\#/cm^3$)
 PDEN — Power of parabolic fall-off in density (= p)
 TEMPØ — Average particle temperature on axis (keV)
 STEMP — Power of parabolic fall-off in temperature (= s)
 QIEDGE — Safety factor at plasma edge ($=q(r = a)$)
 BETAR — Inverse square of standard deviation in poloidal angle ($= \beta$)
 MRPPL — Power of radial fall-off in ripple (= m)
 ZEF — Effective charge
 SIGMA — Vertical elongation ($= \sigma$)
 DEL — Step size in (r/a)
 IMAX — Number of intervals + 1 in r/a
 RMAX — Maximum value of r/a
 CURR — Plasma current (kA)

2. RPPL.DAT: Ripple values for each point of interest at $\theta = 0$, obtained from BFULT and/or BOVAL.

Subroutine GALPHA is used for calculation of the numerical factor, $G(\alpha, \beta; \sigma)$ in the ripple diffusion coefficient due to reduction in the ripple well depth; it takes into account the distortion of the ripple wells caused by the influence of the poloidal angle variation, θ , in the field ripple strength. Use:

CALL GALPHA (ALPHA, BETAR, SIGMA, M, EPS, Q, GAL)

Description of Parameters:

ALPHA — Radial component of $\alpha(r, \theta)$ ($= \alpha(r)$)

EPS — Inverse aspect ratio ($= \varepsilon$)

Q — Safety factor ($= q(r)$)

GAL — Value of $G(\alpha, \beta; \sigma)$

Integration in $G(\alpha, \beta; \sigma)$ is performed by the trapezoidal rule together with Romberg's extrapolation method⁹ in subroutine QATR. Use:

CALL QATR (XL, XU, EPSS, NDIM, FCT, Y, IER, AUX)

Description of Parameters:

XL — The lower bound of the interval

XU — The upper bound of the interval

EPSS — The upper bound of the absolute error

NDIM — The dimension of the auxiliary storage array AUX. NDIM-1 is the maximal number of bisections of the interval (XL, XU)

FCT — The name of the external function subprogram used

Y — The resulting approximation for the integral value

IER — A resulting error parameter

AUX — An auxiliary storage array with dimension NDIM

Remarks: Error parameter IER is coded in the following form:

IER = 0 — It was possible to reach the required accuracy. No error.

IER = 1 — It was impossible to reach the required accuracy because of rounding errors.

IER = 2 — It was impossible to check accuracy because NDIM is less than 5, or the required accuracy could not be reached within NDIM-1 steps. NDIM should be increased.

Listing of RIPPLE is given in Appendix B.

IV. SAMPLE CASE

Figure 2(a) represents the D-shaped TF coil configuration with ①, circular, ②, D-shaped, and ③, elliptical, plasma cross sections. Figure 2(b) shows the calculated poloidal variation of the field ripple size δ of the plasma boundary for the cross sections shown in Fig. 2(a). It can be seen that the maximum ripple for the circular and for the D-shaped plasma occurs at a poloidal angle 0° , whereas for the elliptic cross section for this particular configuration the maximum occurs at poloidal angles near $\pm (55^\circ - 60^\circ)$. For this reason the elliptical plasma is subject to more severe ripple requirements than circular and D-shaped plasmas for a given coil design.

Although RIPPLE code uses input (RPPL.DAT) from BFULT output for ripple values, expressions for the ripple in each case can be given by approximately

$$\begin{aligned}\delta_{\textcircled{1}}(r, \theta) &\cong [\delta_0 + (\delta_a - \delta_0)(\frac{r}{a})^4] \exp[-\beta_{\textcircled{1}}\theta^2] \\ \delta_{\textcircled{2}}(r, \theta) &\cong [\delta_0 + (\delta_a - \delta_0)(\frac{r}{a})^4] \exp[-\beta_{\textcircled{2}}\theta^2] \\ \delta_{\textcircled{3}}(r, \theta) &\cong [\delta_0 + (\delta_a - \delta_0)(\frac{r}{a})^4 (\sigma^2 \sin^2\theta + \cos^2\theta)^2] \cdot \exp[-\beta_{\textcircled{3}}\theta^2],\end{aligned}\tag{9}$$

where a is the plasma minor radius; δ_0 and δ_a are the values of ripple at $r = 0$ and $r = a$, respectively, with $\delta_0/\delta_a = 10^{-13} - 10^{-4}$; and β is a parameter which depends on the shape of the coils and on the plasma location. For this special case $\delta_0 = 6.2 \times 10^{-4}$, $\delta_a = 3.2 \times 10^{-2}$, $\beta_{\textcircled{1}} \cong \beta_{\textcircled{3}} \cong 0.874$, $\beta_{\textcircled{2}} \cong 0.485$ and $\sigma = 1.6$.

$G(\alpha, \beta; \sigma)$, Eq. (7), is calculated numerically and plotted in Fig. 2 for the ①, circular, ②, D-shaped, and ③, elliptic, surfaces shown in Fig. 2(a). The curve $G(\alpha, \beta = 0; \sigma = 1)$ is the result of calculations made by Stringer.⁴ $G(\alpha, \beta; \sigma)$ for the elliptic surface is about an order of magnitude larger because of a peak in δ near $\theta \simeq 55^\circ$. A way to reduce this peak without changing the elongation is to deform the plasma into a D-shape. $G(\alpha, \beta; \sigma)$ for the D-shaped surface is only slightly larger than that for the circular surface. Comparison with the correction factor $I(\alpha)$ obtained by Stringer⁴ and $G(\alpha)$ obtained by Connor and Hastie⁴ shows that where $\beta = 0$, $G(\alpha, \beta; \sigma) \ll I(\alpha)$ or $G(\alpha)$ for all $\alpha(r)$ for ①, circular, and ②, D-shaped, surfaces, that $G(\alpha, \beta; \sigma = 1) \sim I(\alpha)/(10 - 15)$ and $G(\alpha, \beta; \sigma = 1.6) \sim I(\alpha)/(5 - 8)$ for most of the range of interest of $\alpha(r)$.

The ripple-induced ion heat conduction coefficients (Eqs. 5 and 6) were calculated for the typical parameters given in Table I and compared with the total heat conduction loss due to the neoclassical, trapped particle modes, and pseudoclassical coefficients defined in Appendix A.

In the calculation, a parabolic temperature profile, $T = T_0(1 - r^2/a^2)^s$, has been assumed with $n = n_0(1 - r^2/a^2)^p$; the safety factor q is calculated assuming a current density profile that varies like $T^{3/2}$ and given by

$$q(r) = q(a) \frac{(r/a)^2}{[1 - [1 - (r/a)^2]^{3/2s + 1}]} \quad (10)$$

From MHD stability requirement the safety factor q at the plasma boundary must satisfy

$$q(a) > \left(\frac{3}{2} s + 1\right) . \quad (11)$$

Modifications to different plasma parameters and scaling relationships in noncircular cross sections appropriate for large fusion-grade systems are not known; nonetheless estimates were made within the uncertainties posed in Ref. 10. Modeling and predictive capabilities for plasma performance will improve along with our confidence in them as experimental results from PLD, PDX, D-III, ORMAK-Upgrade, etc. become available. Assuming the forms in Appendix A, the results are shown in Figs. 3 and 4 for circular and D-shaped cross sections, respectively. Figure 3 (①, circular cross section) shows that the ion heat conduction coefficients associated with ripple trapping and banana drift are comparable with those calculated from the trapped particle modes if poloidal angle effects are ignored ($\beta = 0$). The inclusion of poloidal angle effects reduces the losses associated with the ripple trapping by a factor of about 10 to 15 but does not change the banana drift losses significantly. As shown in Fig. 4 (②, D-shaped cross section), the results are similar to the circular cross section case except for the inclusion of poloidal angle effects which reduce ripple-trapping losses by a factor of about 5 to 8.

V. SUMMARY AND CONCLUSION

RIPPLE was developed to study the magnetic field ripple effects on plasma transport and on scaling in circular and noncircular tokamaks.

A major question that arises in the design of tokamak devices is the choice of the number of TF coils; this number is determined by

calculating the maximum toroidal field ripple that can be tolerated from plasma physics considerations without seriously restricting the design of the mechanical support system for the blanket and shield, and by the necessity for access to the neutral beam injection. From the plasma physics point of view:

- (1) The overall enhanced heat loss due to ripples should be less than the total heat conduction loss due to neoclassical and trapped particle modes,
- (2) Fast ion losses due to ripple trapping should have no significant effect on power balance, and
- (3) Near the plasma center higher magnetic field ripple might be somewhat desirable for producing a viscous drag on toroidal rotations.²

It should also be noted that enhanced heat loss due to ripples near the plasma edge might help to reduce charge-exchange losses because there is a drop in ion temperature in that region where the neutral population is high. However, this problem should be studied in more detail with 1-D transport simulation models before making a final statement.

In order to optimize the design with tolerable field ripple, acceptable access space, and reasonable cost, it is possible to change: (1) the number of TF coils, (2) the coil bore dimensions, (3) the shape of the TF coils, or (4) the plasma location in the TF coils. Trade-offs among these alternatives should be studied to provide the information necessary for optimization.

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TABLE I
TYPICAL PARAMETERS

Plasma minor radius, $a(m)$	1.0
Major radius, $R(m)$	4.0
Elongation, $(-)$	1.6
Triangularity, $(=d/a)$	0.5
Safety Factor, $q(a)$	5.0
Particle density, $n(cm^{-3})$	1.2×10^{14}
Ion temperature, $T(keV)$	10
Toroidal field coil major radius, (m)	4.0
Inner bore, (m)	3.46×4.66
Outer bore, (m)	4.60×5.80
Current density, $J(A/cm^2)$	1500
Number of TR coils, $N(-)$	20
Magnetic field on axis, $B_T(T)$	6.3
Plasma current, $I(MA)$	3.33

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Fig. 1. Co-ordinate system.

Fig. 2. $G(\alpha, \beta; \sigma)$ versus α for given coil and plasma configuration (a) and ripple variation over the plasma cross section (b), where ①, ②, and ③ represent circular, D-shaped, and elliptic surfaces, respectively.

Fig. 3. Heat conduction coefficients versus plasma radius for a given reference design (circular).

Fig. 4. Heat conduction coefficients versus plasma radius for a given reference design (D-shaped).

APPENDIX A

The expressions used in the calculations, neoclassical (NC), trapped particle modes [trapped ion mode (TIM) and trapped electron mode (TEM) 1 or 2, whichever is smaller], and pseudoclassical (PS) coefficients, are given below for $T_e = T_i^{10}$:

$$\chi_i^{NC} \simeq \epsilon^{-3/2} q^2 \rho_e^2 v_{ei} (m_i/m_e)^{1/2} \left(\frac{1+\sigma^2}{2}\right)^{-1}$$

$$\chi_e^{TIM} = \chi_i^{TIM} \simeq \frac{\epsilon^{5/2}}{4} \frac{v_{drift}^2}{v_{ei}} (R/r_n)^2 \left(\frac{1+\sigma^2}{2}\right)^{-1}$$

$$\chi_e^{TEM1} \simeq 3 \epsilon^{3/2} \frac{v_{drift}^2}{v_{ei}} \left[\frac{R^2}{r_n r_T}\right] \left(\frac{1+\sigma^2}{2}\right)^{-1}$$

$$\chi_e^{TEM2} \simeq C (q^2/\epsilon^2) \rho_e^2 v_{ei} \left(\frac{1+\sigma^2}{2}\right)^{-1}$$

$$\chi_e^{PS} \simeq 10 (q^2/\epsilon^2) \rho_e^2 v_{ei} \left(\frac{1+\sigma^2}{2}\right)^{-1}$$

$$\chi_e^{[EMP]1} \simeq 10^3 \left(\frac{I_T(\text{kA})}{120}\right) \left(\frac{2 \times 10^{13}}{n}\right)^2 f(r)$$

$$\chi^{[EMP]2} \simeq K q^{-1/2} n^{-1},$$

where $r_n = [\frac{1}{n} \frac{dn}{dr_\psi}]^{-1}$, $r_T = [\frac{1}{T} \frac{dT}{dr_\psi}]^{-1}$, ρ_e is the electron Larmor radius in the toroidal field, $C \simeq 0.06 \epsilon^{\frac{1}{2}} (d \ln T / d \ln n) (m_i / m_e) (B_\theta / \Theta B_T)$, $\Theta = r_n / L_s$,

$L_s^{-1} \simeq (\frac{1 + \sigma^2}{2})^{\frac{1}{2}} \frac{r}{q^2 R} \frac{\partial q}{\partial r_\psi}$, $B_\theta \simeq \frac{\epsilon}{q} B_T \sqrt{\frac{1 + \sigma^2}{2}}$ is the average poloidal field,

$I_T \simeq \frac{2\pi a^2}{\mu_0 q R} B_T (\frac{1 + \sigma^2}{2})$ is the average plasma current, $f(r)$ is profile function, $v_{ei} = 1.6 \times 10^4 Z_{eff} (n/10^{13}) / T_e^{3/2} (\text{keV})$, and q is the safety factor.

APPENDIX B

RIPPLE COMPUTER CODE LISTING

```

C
C THIS PROGRAM CALCULATES THE ION HEAT CONDUCTION LOSSES
C FOR CIRCULAR AND NON-CIRCULAR PLASMAS.
C
C *****
C T = TEMP0*(1. - X**2)**S          IN KEV
C N = DEN0*(1. - X**2)**S          IN #/CM**3
C Q1 : SAFETY FACTOR AT PLASMA EDGE
C SIGMA : ELONGATION
C RMAJOR : MAJOR RADIUS IN CM
C RMINOR : MINOR RADIUS IN CM
C BMAG : MAGNETIC FIELD IN KGAUSS
C ZEF : EFFECTIVE CHARGE
C NCOIL : # OF COILS
C M = MRPPL : POWER OF RADIAL COMPONENT(FOR RIPPLE)
C BETAR : POLOIDAL ANGLE COEFFICIENT(0.5 .....1.0)
C DEL : STEP SIZE IN R/A
C RMAX : MAXIMUM VALUE OF R/A
C NOTE THAT : ***** IN GALPHA *****
C FOR ELLIPTICAL PLASMA TAKE A(1)/FACTOR(1)
C AND A(I+1)/FACTOR(I+1) WHERE
C FACTOR(I) = (SIG2*SIN(TH(I))**2 + COS(TH(I))**2)**.5
C AT FNK *****
C FOR AN ELLIPTICAL PLASMA TAKE
C F9 = (SIG2*SIN(X)**2 + COS(X)**2)**.5
C *****
C XBD : BANANA DRIFT HEAT CONDUCTION COEF.
C XNC : NEOCLASSICAL
C XA : PSEUDECLASSICAL
C XB OR XC : TRAPPED ELECTRON MODE 1 OR 2
C XD : TRAPPED ION MODE
C XRPPL : RIPPLE - TRAPPED
C XTEM : MINIMUM OF (XB,XC)
C XE1 : EMPIRICAL(ORMAK DATA)
C XE2 : EMPIRICAL(ALCATOR)
C
C
C NOTE : FOR INPUT AND OUTPUT DATA WE HAVE
C FOR20.DAT : INPUT NAMELIST DATA(DATA.RPL)
C FOR21.DAT : RIPPLE VALUES FOR EACH POINT OF INTEREST.
C (RPPL.DAT)
C FOR22.DAT : OUTPUT
C *****
C DIMENSION RA(200),RPPL(200)
C
C NAMELIST/ DATA/RMAJOR,RMINOR,BMAG,NCOIL,DEN0,PDEN,TEMP0,
C 1STEMP,Q1EDGE,BETAR,MRPPL,ZEF,SIGMA,DEL,IMAX,RMAX,CURR
C
C READ(20,DATA)
C WRITE(22,8)
C 8 FORMAT(/,5X,'INPUT DATA *****',/)
C WRITE(22,DATA)
C WRITE(22,11)
C 11 FORMAT(/,5X,'*****')
C
C PI = 3.14159
C RM = 1.0/1836.0
C ALPH1 = 66.7146
C H = 0.05176

```

```

RR = RMINOR/RMAJOR
B0 = BMAG
SIGM = SIGMA
TEMP = TEMP0
N = NCOIL
M = MRPPL
C = N
PM = M
P = PDEN
S = STEMP
Q1 = Q1EDGE
SM = 0.5*(1.0 + SIGM*SIGM)
RA(1) = 0.0
3 READ(21,3) (RPPL(I) , I=1,IMAX)
  FORMAT(8X,E13.6)
  WRITE(22,3) (RPPL(I) , I=1,IMAX)

```

```

C
DO 12 I = 2,IMAX
  RI = I - 1
  RA(I) = DEL*RI
  IF(RA(I) .GT. RMAX) GO TO 14
  EPS = RA(I)*RR
  EPS3 = EPS*SQRT(EPS)
  DEN = DEN0*(1. - RA(I)**2)**P
  TI = TEMP*(1.0 - RA(I)**2)**S
  Q = Q1*RA(I)**2/(1. - (1.-RA(I)**2)**(1.5*S+1.))
  RQ = 2.*(1. - (1.5*S+1.)*(1.-RA(I)**2)**(1.5*S))*Q/Q1)

```

```

C
  ALPHA = EPS/(Q*C*RPPL(I))
  CALL GALPHA(ALPHA,BETAR,SIGMA,M,EPS,Q,GAL)
  YG = GAL
  REI = 1.6E04*ZEF*(DEN*1.0E-13)/(SQRT(TI)*TI)
  RII = REI*SQRT(RM)
  VT = 1.0E07*SQRT(20.0*TI)
  RE = SQRT(RM)*SQRT(20.0*TI/B0**2)
  VDR = 1.0E08*TI/(B0*RMAJOR)
  RETH = RE*Q/EPS
  PRFL = RMINOR*(1.0 - RA(I)**2)
  DNDR = - 2.*P*RA(I)/PRFL
  DTDR = S*DNDR/P
  RN = 1.0/ABS(DNDR)
  RT = 1.0/ABS(DTDR)
  RPS = S/P
  RLS = RMAJOR*Q/(RQ*RN)
  RNRT = 1.0E16*TI*TI/(B0*B0*RN*RT)
  RNR = 1.0E08*TI/(B0*RN)
  C2 = 0.06*SQRT(EPS)*RPS*(EPS/Q)*RLS/RM

```

```

C
C
  XBD = 4.0*(SQRT(2.0/PI))*(2.0/PI)*ALPH1*RQ*RQ*C*(RPPL(I)**2)
1  *EPS3*VDR*VDR*H*Q*Q/(RII*(PM + 2.))*2*SIGM**2)
  XNC = Q*Q*RE*RE*RII/(SM*EPS3*RM)
  XA = 10.0*REI*RETH*RETH/SM
  XC = C2*REI*RETH*RETH/SM
  XB = 3.0*EPS3*RNRT/(SM*REI)
  XD = EPS*EPS3*RNR*RNR/(SM*REI)

```

```

XRPPL = 46.5*SQRT(RPPL(I))*RPPL(I)*YG*VDR*VDR/(RII*SIGM*SIGM)
XTEM = AMIN1(XB, XC)
XE1 = 3.33E28*CURR*(1. + 4.*RA(I))/(DEN0**2)
XE2 = 7.8E17/(SQRT(Q1EDGE)*DEN)

```

C

```

WRITE(22,15) RA(I), RPPL(I), XE1, XE2
15 FORMAT(/,5X,'R/A=',G15.5,3X,'RIPPLE=',G15.5,3X,'XE1=',
1G15.5,3X,'XE2=',G15.5/)

```

```

WRITE(22,18) XA,XB,XC,XTEM,XD,XBD,XNC,XRPPL
18 FORMAT(/,5X,'XPS = ',G15.5,5X,'XB = ',G15.5,5X,'XC = ',G15.5,5X,'
1XTEM = ',G15.5/,4X,'XTIM = ',G15.5,4X,'XBD = ',G15.5,4X,'XNC = ',
1G15.5,4X,'XRIPPLE = ',G15.5/)
12 WRITE(22,16)
16 FORMAT(/, '*****',/)
14 CONTINUE
STOP
END

```

C

```

SUBROUTINE GALPHA(TLPHA,BETAR,SIGMA,M,EPS,Q,GAL)

```

C

```

THIS PROGRAM CALCULATES G(ALPHA)

```

C

```

*****
THIS PROGRAM CALCULATES THE NUMERICAL FACTOR IN RIPPLE
DIFFUSION COEFFICIENT DUE TO REDUCTION IN RIPPLE
WELL DEPTH. NOTE: BETAR = 0 GIVES STRINGER'S RESULT.
*****
*****

```

C

```

COMMON/RFNX/ALPHT,RB,MM,SIG2,AA
DIMENSION TH(600),Y(600),AUX(210),A(600)

```

C

```

EXTERNAL FNX

```

C

```

PI = 3.14159
DEL2 = 0.50
DELR = DEL2*PI/180.0
MM = M/2
SIGM = SIGMA
RB = BETAR
SIG2 = SIGM*SIGM
AA = EPS*(SIG2 - 1.0)/(Q*Q)
ALPHT = TLPHA
EPSS = 0.10E-04
NDIM = 201

```

C

```

ALP2 = TLPHA*TLPHA
GO TO 14

```

C

```

10 XL = 0.0
XU = PI
CALL QATR(XL,XU,EPSS,NDIM,FNX,Z,IER,AUX)
IR1 = IER
GAL = 2.0*Z/PI
GO TO 20

```

C

```

14 TH(1) = 0.0
A(1) = EXP(RB*TH(1)**2)

```

```

      Y(1) = 1.0 - ALP2*(SIN(TH(1))**2)*(A(1)**2)
1     *((1.0 - AA*COS(TH(1)))**2)
      DO 15 I = 1,500
      TH(I+1) = TH(1) + DELR
      IF(TH(I+1) .GE. PI) GO TO 10
      A(I+1) = EXP(RB*TH(I+1)**2)
      Y(I+1) = 1.0 - ALP2*(SIN(TH(I+1))**2)*(A(I+1)**2)
1     *((1.0 - AA*COS(TH(I+1)))**2)
      YM = Y(I)*Y(I+1)
      IF(YM) 16,16,15
15    CONTINUE
16    THC = TH(I+1)-DELR*Y(I+1)/(Y(I+1) - Y(I))
      XL = 0.0
      XU = THC
      TH1 = THC*180./PI
      CALL QATR(XL,XU,EPSS,NDIM,FNX,Z,IER,AUX)
      IR2 = IER
      G1 = 2.0*Z/PI
C
      TH(1) = PI
      A(1) = EXP(RB*TH(1)**2)
      Y(1) = 1.0 - ALP2*(SIN(TH(1))**2)*(A(1)**2)
1     *((1.0 - AA*COS(TH(1)))**2)
      DO 18 I = 1,500
      TH(I+1) = TH(1) - DELR
      A(I+1) = EXP(RB*TH(I+1)**2)
      Y(I+1) = 1.0 - ALP2*(SIN(TH(I+1))**2)*(A(I+1)**2)
1     *((1.0 - AA*COS(TH(I+1)))**2)
      YM = Y(I)*Y(I+1)
      IF(YM) 21,21,18
18    CONTINUE
21    THC = TH(I+1) - DELR*Y(I+1)/(Y(I+1) - Y(I))
      XL = THC
      XU = PI
      TH2 = THC*180./PI
      CALL QATR(XL,XU,EPSS,NDIM,FNX,Z,IER,AUX)
      IR3 = IER
      G2 = 2.0*Z/PI
      GAL = G1 + G2
20    CONTINUE
      RETURN
      END
C
      SUBROUTINE QATR(XL,XU,EPSS,NDIM,FCT,Y,IER,AUX)
C
C     *****
C     THIS PROGRAM CALCULATES INTEGRAL IN GALPHA.
C     NOTE THAT:
C     IF IER = 0 ; IT WAS POSSIBLE TO REACH REQUIRED ACCURACY.
C     IF IER = 1 ; IT IS IMPOSSIBLE TO REACH REQUIRED ACCURACY.
C     IF IER = 2 ; IT WAS IMPOSSIBLE TO CHECK ACCURACY.
C     NDIM SHOULD BE INCREASED.
C     *****
C     DIMENSION AUX(1)
C
C     PREPARATION OF ROMBERG-LOOP
      AUX(1) = .5*(FCT(XL) + FCT(XU))
      H = XU - XL
      IF(NDIM - 1) 8,8,1

```



```

1  IF(H) 2,10,2
C
C  NDIM IS GREATER THAN 1 AND H IS NOT EQUAL TO 0.
2  HH = H
   E = EPSS/ABS(H)
   DELT2 = 0.
   P = 1.
   JJ = 1
   DO 7 I=2,NDIM
     Y = AUX(I)
     DELT1 = DELT2
     HD = HH
     HH = .5*HH
     P = .5*P
     X = XL + HH
     SM = 0.
     DO 3 J=1,JJ
       SM = SM + FCT(X)
3    X = X + HD
     AUX(I) = .5*AUX(I-1) + P*SM
C    A NEW APPROXIMATION OF INTEGRAL VALUE IS COMPUTED BY MEANS OF
C    TRAPEZOIDAL RULE.
C    START OF ROMBERGS EXTRAPOLATION METHOD.
     Q = 1.
     JI = I-1
     DO 4 J=1,JI
       II = I-J
       Q = Q + Q
       Q = Q + Q
4    AUX(II) = AUX(II+1) + (AUX(II+1) - AUX(II))/(Q-1.)
C    END OF ROMBERG-STEP
C
     DELT2 = ABS(Y - AUX(1))
     IF(I-5) 7,5,5
5    IF(DELT2 - E) 10,10,6
6    IF(DELT2 - DELT1) 7,11,11
7    JJ = JJ + JJ
0    ICR = 2
9    Y = H*AUX(1)
   RETURN
10  IER = 0
   GO TO 9
11  IER = 1
   Y = H*Y
   RETURN
END

C
C  FUNCTION FNX(X)
C  *****
C  FUNCTION UNDER INTEGRAND.
C
COMMON/RFNX/ALPHT,RB,MM,SIG2,AA

C
PI = 3.14159
ALPHA = ALPHT

C
F1 = RB***X
F2 = EXP(-F1)
F9 = 1.0

```

```
F10 = 1.0 - AA*COS(X)
F3 = ALPHA*F10*SIN(X)/(F2*F9)
F4 = ABS(F3)
IF(F4 .GT. 1.0) F4 = 1.0
F5 = SQRT(1.0 - F4**2)
F6 = 0.50*PI - ASIN(F4)
F7 = (F5 - F4*F6)**3
F8 = (F2*F9)**3
FNX = SIN(X)*SIN(X)*SQRT(F8)*SQRT(F7)*F10*F10
RETURN
END
```

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