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EFFECT OF MAGNETIC FIELD RIPPLE ON DIFFUSION IN TOKAMAKS

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ABSTRACT

The magnetic field modulation due to the discrete nature of the field coils in a Tokamak leads to additional particle trapping. The resulting diffusion is evaluated and compared with neoclassical. The two diffusion rates are found to be comparable in existing Tokamaks. The limit on the field ripple below which ripple diffusion should be negligible in next generation machines is evaluated.

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1. INTRODUCTION

The axisymmetry of the magnetic field has been considered one of the main advantages of Tokamaks. Besides greatly simplifying the analysis, the radial excursions of trapped particles at low collision frequencies is less than in asymmetric fields. In practice the discrete nature of the magnetic field coils leads to a ripple in the field strength, with period equal to the distance between coil centres. This spoiling of the symmetry has generally been assumed to be negligible. Whether or not this is true in existing Tokamaks, its effect is likely to be more important in the next generation of machines for two reasons. It is hoped that these will achieve higher temperature, and the effect of asymmetry increases as the collision frequency decreases. Further, because of the more advanced coil construction used, or because of access required for neutral injection, it may be impractical to reduce the ripple simply by decreasing the gaps between coils.

Several papers[1,2] have pointed out that the effect of field ripple is qualitatively similar to that of the helical field variation in a stellarator. This has been confirmed by a formal derivation of the diffusion in a ripple magnetic field using the variational principle[3]. Practical techniques for minimising the asymmetric field variation over a magnetic surface by coil design have been proposed in Ref.4. The present paper evaluates the particle diffusion and thermal diffusivity, and estimates the effect on the overall containment times in practical Tokamak devices.

The depth of the magnetic wells in a rippled toroidal field is derived as a function of poloidal angle in Sec.2. The heuristic arguments developed to illuminate the physical origin of stellarator diffusion are applied to the rippled field in Sec.3. This leads to a number of collisional regimes, each characterised by a simple analytic expression for the diffusion. It is apparent that the most relevant regime for next generation Tokamaks is that in which the ripple diffusion varies inversely as the collision frequency. The corresponding analytic expressions derived for a stellarator are used in Sec.4 to evaluate the local coefficients of diffusion and thermal diffusivity. The ripple diffusion is compared with that resulting solely from the toroidal variation in Sec.5, leading to estimates of the maximum acceptable field ripple.

2. MAGNETIC WELL DEPTH

Superimposing a ripple on the simple magnetic field model commonly used in Tokamak analysis gives a field strength which varies as

$$B \simeq B_\varphi = B_0\,[1-\varepsilon\cos\theta-\delta(r)\cos N\varphi] \qquad (1)$$

where θ is the poloidal angle around the magnetic axis, φ measures angular distance around the axis of symmetry, r is the radial distance from the magnetic axis, R is the radius of the magnetic axis, $\varepsilon = r/R$ is the inverse aspect ratio, $2\delta(r)B_0$ is the magnitude of the field ripple over the magnetic surface r = constant, and N is the number of coils in the B_φ winding. In practice the ripple modulation δ will depend on θ. Such a dependence can readily be included in the later analysis, but should not be strong for a coil designed to reduce ripple. The corrugation of the magnetic surfaces, $\Delta r = -\cos N\varphi \int_0^r \delta(r)dr$, has negligible effect on the magnetic well depth.

The variation in field strength along a field line is

$$\frac{1}{B_0}\ \frac{\partial B}{\partial s} = \frac{1}{R}\left(\frac{\varepsilon}{q}\sin\theta + \delta N \sin N\varphi\right) \tag{2}$$

since $d\theta/d\varphi = B_\theta/\varepsilon B_\varphi = 1/q$. The usual Tokamak ordering is assumed, i.e., $\varepsilon \ll 1$, $q = O(1)$, $N \gg 1$. Thus the variation in B along a field line appears as a short wavelength ripple superimposed on the slower toroidal variation. Since the variation in θ over one ripple period is small, the condition for a ripple well to occur, given by $\partial B/\partial s = 0$, is[4] $\delta > (\varepsilon/qN)\ |\sin\theta|$. When this condition is satisfied a minimum occurs at $N\varphi = 2m\pi - \sin^{-1}(\alpha\sin\theta)$, with adjacent maxima at $N\varphi = (2m \pm 1)\pi + \sin^{-1}(\alpha\sin\theta)$, where $\alpha = \varepsilon/qN\delta$ and m is any integer less than N. The magnetic well depth is determined by the difference between the minimum field strength and the lower of the two adjacent maxima. This difference is ΔB_0 where

$$\Delta(\theta) = \frac{B_{max}-B_{min}}{B_0} = 2\delta\left[\sqrt{1-\alpha^2\sin^2\theta} - \alpha\left\{\frac{\pi}{2} - \sin^{-1}(\alpha|\sin\theta|)\right\}|\sin\theta|\right] \tag{3}$$

and θ is the poloidal angle of the field line as it intersects the plane $N\varphi = 2m\pi$.

3. HEURISTIC DISCUSSION OF THE DIFFUSION

The variation in magnetic field strength along a field line is qualitatively the same as in a stellarator. The following discussion makes extensive use of the physical arguments used by Gibson & Mason[5] to estimate the diffusion in a stellarator and extended by Kadomtsev and Pogutse[1] in their recent review.

The magnitude of ripple of experimental interest is not more than a few per cent at the plasma boundary r = a, and decreases towards the magnetic axis. The inverse aspect ratio is typically $\varepsilon = 0.2\ r/a$. Hence $\delta < \varepsilon$ except near the magnetic axis. We will first consider the case of zero radial electric field and $\alpha \ll 1$. The ripple well depth is then approximately 2δ, independent of θ.

The condition for particles to be trapped within the ripple well is $R/N\lambda < \delta^{\frac{3}{2}}$, where λ is the mean free path. This follows from the usual argument[1] that the scattering time out the trapped velocity band $|v_{\parallel}/v_{\perp}| < \delta^{\frac{1}{2}}$, which is $\tau_s = \delta/\nu$, must be longer than the transit time across the well, $R/Nv_{\parallel}$. Over the collisional range defined by $\delta^{3/4}\, \rho_j/a < R/\lambda < N\delta^{\frac{3}{2}}$, where ρ_j is the Larmor radius and j denotes the species, the ripple diffusion may be deduced from the following random-walk argument. The dominant radial drift, resulting from the toroidal variation in magnetic field strength, is $v_r = V_{\perp} \sin\theta$, where $V_{\perp} \approx T_{\perp}/eBR$. For a passing particle, the periodic variation in sign of this drift produces a net horizontal shift of its orbit relative to a magnetic surface. Each time a particle enters the ripple trapping band, however, it remains localised at a constant θ value for a time of order τ_s, during which it suffers a radial displacement of $\Delta r = (V_{\perp}\delta/\nu)\sin\theta$. The number of particles passing through the ripple trapping band is $n\nu/\delta^{\frac{1}{2}}$ per second. Regarded as a random walk process, these large radial displacements give rise to a diffusion coefficient

$$D_1 \sim \frac{\nu}{\delta^{\frac{1}{2}}} \left(\frac{V_{\perp}\delta}{\nu}\right)^2 = \frac{\delta^{3/2}\, V_{\perp}^2}{\nu} . \tag{4}$$

When $R/\lambda < \delta\rho_j/a$, then $\Delta r > a$, i.e., the ripple trapped particles drift to the walls without being scattered out of the trapped velocity band. A loss cone develops and the containment time is then comparable to the 90^0 scattering time. This corresponds to a diffusion coefficient $D \sim \nu a^2$. If $\delta > \varepsilon$ had been assumed, the poloidal rotation of a ripple banana, due to the ripple field gradients, would cause $\sin\theta$ to change sign before the banana had time to reach the wall.

This would produce a superbanana orbit, analogous to those in a stellarator whose helical modulation in field strength exceeds its inverse aspect ratio.

In the intervening range $\delta\rho_j/a < R/\lambda < \delta^{3/4}\ \rho_j/a$, the ripple trapped particles escape by a random walk process since $\Delta r < a$. However, the escape rate of these particles is so rapid that collisions are unable to maintain the density of trapped particles at the Maxwellian value, and a dip occurs in the velocity distribution. Over this narrow range, the diffusion coefficient should be approximately independent of collision frequency.

The above variation of diffusion with collision frequency is illustrated in Fig.1. The same figure shows the diffusion in a comparable axisymmetric Tokamak. When $\delta \ll \varepsilon$, the total trapped particle diffusion in the rippled toroidal field approximately equals the sum of the two rates. The justification for this is as follows. When $qR/\lambda < \varepsilon^{\frac{3}{2}}$, those particles whose velocities lie in the band $|v_{\parallel}/v_{\perp}| < \varepsilon^{\frac{1}{2}}$ are trapped in the toroidal field and on average spend a time ν/ε before being scattered out. During this time they may go round their banana orbit several times. On one or more occasions their velocity enters the ripple trapping band. When this happens, the motion round the banana is halted for a time of order δ/ν. During this time the particle suffers a radial displacement of order $V_{\perp}\delta/\nu$. This is additional to the mean displacement of one banana width each time the particle passes through the toroidal trapping band. Hence the overall displacement of a typical particle per unit time is

$$\delta r = \sum \nu_{eff}(\Delta r)^2 = \frac{\nu}{\delta^{\frac{1}{2}}}\left(\frac{V_{\perp}\delta}{\nu}\right)^2 + \frac{\nu}{\varepsilon^{\frac{1}{2}}}\ (\varepsilon^{\frac{1}{2}}\rho_{j\theta})^2$$

where $\rho_{j\theta}$ is the Larmor radius in the B_θ field.

As the collision frequency decreases, ripple trapping sets in before toroidal trapping if $Nq > (\varepsilon/\delta)^{\frac{3}{2}}$. Taking as typical values, $N = 16$, $q = 3$, $\varepsilon = 0.2$, this is satisfied if $\delta > 0.015$. An order of magnitude comparison shows that when ripple and toroidal trapping both occur, ripple diffusion dominates over pure toroidal diffusion if $R/\lambda < (\delta\varepsilon)^{3/4}/q$.

We will now briefly consider the effect of radial electric field. The foregoing arguments would predict quite different diffusion rates for ions and electrons. From the more complete analysis one knows that to obtain the diffusion in the presence of a radial electric field one must multiply the above diffusion coefficients by

$$\frac{dn}{dr} + \frac{ne_j}{T_j} E_r + \gamma_j \frac{n}{T_j} \frac{dT_j}{dr}$$

where γ_j is a numerical factor of order unity. Thus an ambipolar electric field is set up which reduces the escape rate of the faster diffusing species to that of the slower. One thus expects a radial potential $|\Phi| \sim O(T/e)$. We now consider whether the presence of this electric field will seriously affect the slower diffusing species.

The loss cone, which in the absence of electric field occurs at very low collision frequencies, should be eliminated by a potential $\Phi \gtrsim O(\varepsilon T/e)$. The radial excursion of a ripple banana is then limited to $\Delta r \sim V_\perp/\omega_E$, where $\omega_E = E_r/rB$ is the poloidal rotation frequency. The qualitative expressions deduced by Kadomtsev and Pogutse[1] for a stellarator field can equally be applied to a rippled field, giving the following predictions. When $\nu > \delta\omega_E$ the radial excursion of a ripple banana is limited by collisions and Eqn.(4) is still valid. When $\omega_E(\varepsilon T/e)^4 < \nu < \delta\omega_E$, the ripple diffusion is[6]

$$D_R \sim \varepsilon^2 \left(\frac{\nu}{r}\right)^{\frac{1}{2}} \left(\frac{T}{eE_r}\right)^{\frac{3}{2}} \left(\frac{T}{eB}\right)^{\frac{1}{2}} . \tag{5}$$

When the collision frequency lies below the lower limit of the above range, a loss cone develops and the confinement time is then limited to a 90° scattering time.

We will now consider which parameter ranges are relevant to existing and next generation Tokamaks. The following simple form will be assumed for the radial profiles; $n(r) = n_o(1 - x^2)$, $T_e = T_{eo}(1 - x^2)$, $T_i = T_{io}(1 - x^2)$, $\delta(r) = \delta_a x^2$, where $x = r/a$. The above radial variation of $\delta(r)$ is unrealistic at small x, since the field ripple does not vanish on the magnetic axis. However, as will be seen later, the ripple diffusion near axis is negligible compared to the toroidal component. Typical parameters for existing Tokamaks, i.e. T-3 and ST, are $n = 3 \times 10^{13}/cm^3$, $T_{eo} = 1$ keV, $T_{io} = 500$ eV, $B_\varphi = 30$ kG, a = 12 cm, R = 100 cm. The following values are typical of the parameters expected in next generation Tokamaks; $n_o = 10^{14}/cm^3$, $T_{eo} = T_{io} = 3$ keV, $B_\varphi = 35$ kG, a = 65 cm, R = 195 cm. These two sets of parameters will be referred to as conditions (a) and (b) respectively. The number of field coils is assumed to be 16 in both cases. We first evaluate the condition that the ion banana excursions are limited by collisions, rather than electric drift. This condition is $\nu_i > \delta\omega_E$, which can be expressed in the more convenient form $\delta < 10^{-14} nBrr_n/T_i^{5/2}$ where T_i is in eV, B in gauss, r_n is the density scale length, and $|E_r| = T_i/er_n$ is assumed. This condition is well satisfied with field ripples of interest in existing and next generation devices. The range of validity of Eqn.(4) for the ions can be expressed in practical units as $145\ \delta^{3/4}\ T_i^{\frac{1}{2}}/aB < 10^{-12}\ nR/T_i^2 < N\delta^{3/2}$. Taking $\delta_a = .03$ as typical of existing Tokamaks, and other parameters as for condition (a), this requires $0.5 < r/a$. Thus Eqn.(4) should apply over the outer regions which largely determine the containment time. Substituting the next generation parameters into the above condition gives $.004 < \delta(r) < 1$. Even with the minimum field ripple achievable, this will be satisfied over much of the cross-section.

4. EVALUATION OF THE DIFFUSION

From the previous section it appears that existing and next generation Tokamaks will operate mostly in the regime where ripple trapping occurs and where the ripple diffusion is described qualitatively by Eqn.(4). The aim of this section is to evaluate the numerical coefficient multiplying this expression, relaxing the assumption $\alpha \ll 1$ made in the earlier heuristic derivations.

The most comprehensive expressions for the ambipolar diffusion and ion heat transport in this regime have been derived by Connor(7).

$$\Gamma_a = \frac{4.1}{\nu_{ei}}\ \delta^{\frac{3}{2}} \left(\frac{T_e}{eBR}\right)^2 \left[\left(1 + \frac{T_i}{T_e}\right)\frac{dn}{dr} + \frac{7}{2}\frac{n}{T_e}\frac{d}{dr}\left(T_e + T_i\right)\right] \qquad (6)$$

$$Q_i = \frac{40.6}{\nu_{ii}}\ \delta^{\frac{3}{2}} \left(\frac{T_i}{eBR}\right)^2 n\ \frac{dT_i}{dr} \qquad (7)$$

where

$$\nu_{ji} = \frac{4}{3}\ \frac{\sqrt{2\pi}\ ne^4}{m_j^{\frac{1}{2}}\ T_j^{\frac{3}{2}}}\ \ell n\ \Lambda$$

Γ_a is the mean particle flux per unit area of either species across a magnetic surface and Q_i the mean ion heat flux. Eqn.(6) generalises earlier results(2,8), derived for a stellarator but equally applicable to a rippled toroidal field, in that the temperature gradient is included and the derivation does not assume $\delta > \varepsilon$. In deriving

Eqn.(6) and (7), the depth of the ripple wells $(B_{max} - B_{min})/B_o$ was taken to be 2δ, independent of poloidal angle. We shall now extend these results to include the variation in well depth with poloidal angle found in Sec.2.

Ripple diffusion is a localised process in the sense that, during the time a particle is contributing, it is localised within one ripple period. Thus its motion is determined by the depth of the local well, and it is unaware of the variation of well depth over the magnetic surface. It is therefore a reasonable approximation to replace the constant well depth in earlier evaluations of the velocity distribution over a magnetic surface by $\Delta(\theta)$. This ignores the change in shape and width of the magnetic well. After integration over a magnetic surface, the resulting particle and heat fluxes differ from Eqn.(6) and (7) by a factor

$$J = \frac{1}{\pi}\int\left(\frac{\Delta}{2\delta}\right)^{3/2} \sin^2\theta \, d\theta$$

$$= \frac{4}{\pi\alpha^2}\int_0^c \frac{y^2}{\sqrt{\alpha^2 - y^2}}\left[\sqrt{1 - y^2} - y\left(\frac{\pi}{2} - \sin^{-1} y\right)\right]^{3/2} dy \qquad (8)$$

where $y = \alpha \sin\theta$. The upper limit of integration is $c = \alpha$ when $\alpha < 1$, and $c = 1$ when $\alpha > 1$. The computed value of J is plotted in Fig.2. The integral may be evaluated analytically when $\alpha \ll 1$ by expanding in powers of y, except in $(\alpha^2 - y^2)^{\frac{1}{2}}$. This gives

$$J = 1 - 2\alpha + 1.26\,\alpha^2 + 0(\alpha^3)\cdot \qquad (9)$$

When $\alpha \gg 1$ the computed value is approximately $J \sim \cdot 0335/\alpha^3$. Even when $\alpha < 1$, the diffusion is reduced by up to an order of magnitude compared to previous estimates. This results from the reduction in the ripple well depth by the superposition of the toroidal variation. The change in well depth is small near $\theta = 0$ and π, but here the radial component of the drift velocity is also small. The effect is greatest near $\theta = \pi/2$ and $3\pi/2$, where the drift velocuty is predominantly radial. As α increases beyond unity, ripple trapping becomes restricted to a progressively narrower range of poloidal angles around $\theta = 0$ and π.

5. NUMERICAL EVALUATION OF THE TRANSPORT COEFFICIENT

The variation of the ambipolar diffusion coefficient and ion thermal diffusivity with radius is shown in Fig.3-6 for the two sets of typical parameters given in Sec.3. In both cases the inverse rotational transform, $q(r)$, is taken equal to $3/(3 - 2x)$. This corresponds to a current profile of the form $j_\varphi(r) = j_o(1 - x)$, and of magnitude such that $q(r) \geqslant 1$ everywhere. Fig.3 and 4 are calculated for condition (a), with $\delta_a = {\cdot}03$. The ripple magnitude is more commonly expressed as the total percentage variation over the outer surface, i.e. 6% in this example. Fig.5 and 6 are evaluated for the parameters typical of next generation Tokamaks, and $\delta_a = {\cdot}01$, ${\cdot}02$, or ${\cdot}04$.

The ripple diffusion coefficient, plotted in Fig.3 and 5, is obtained by multiplying the right hand side of Eqn.(6) by $J(\alpha)/(dn/dr)$. In condition (a), $\alpha = {\cdot}0835(3 - 2x)/x$. This is small, except near the axis, and so the factor $J(\alpha)$ is close to unity,i.e., the reduction in ripple well depth due to superposition of the toroidal variation in field strength is small. To illustrate how important this effect is in condition (b), where α can be quite large, the predicted diffusion when the factor $J(\alpha)$ is omitted is shown in Fig.5 by dashed lines for $\delta_a = {\cdot}01$ and ${\cdot}04$. The neo-classical banana diffusion coefficient[9,10] is also plotted in Fig.3 and 5, using the numerical coefficients derived in Ref.(10) for an axisymmetric system.

The ripple thermal diffusivity plotted in Fig.4 and 6 is obtained by multiplying the right hand side of Eqn.(7) by $J(\alpha)/n(dT_i/dr)$. Since the reduction in diffusivity resulting from the effect of toroidal variation on the ripple well depth is the same as for the diffusion coefficient, the corresponding curves without the $J(\alpha)$ factor are not shown in Fig.6. The neo-classical (banana) thermal diffusivity[9,10] is again shown for comparison.

In the existing Tokamak condition, the predicted ripple diffusion exceeds the toroidal contribution over much of the cross-section, while the ripple ion thermal diffusivity is everywhere less than the toroidal. In next generation Tokamaks, however, the ripple contribution dominates the ion thermal diffusivity over a wider range than it dominates the diffusion. This difference results from the differing values of T_i/T_e. For the ripple contributions $\chi_{iR}/D_R \sim 2(m_i/m_e)^{\frac{1}{2}}\ (T_i/T_e)^{7/2}\ (1+T_i/T_e)^{-1}$ while for the toroidal banana contributions $\chi_{ib}/D_b \sim 0.5(m_i/m_e)^{\frac{1}{2}}\ (T_e/T_i)^{\frac{1}{2}}(1+T_i/T_e)^{-1}$. Hence χ_{iR} is relatively less important in the existing Tokamak condition, where $T_i/T_e \sim 0.5$, than in the next generation condition which assumes $T_i = T_e$.

6. CONCLUSIONS

The effect of field ripple on the trapped particle diffusion in a Tokamak resembles the effect of the helical field variation in a stellarator. A straightforward translation of the stellarator analysis to a rippled toroidal field suggests that it would be difficult to prevent an appreciable reduction in containment time in these experiments below the neo-classical value, while maintaining the required access for neutral injection. For a weak ripple, however, the depth of the ripple wells is reduced by the superposition of the toroidal variation in field strength. This greatly reduces the ripple diffusion for small δ. There is no analogous effect in a stellarator since here the toroidal variation along a field line, which is proportional to rotational transform, decreases more rapidly than the depth of the helical modulation.

For a particular set of parameters, typical of next generation Tokamaks, the calculated ripple diffusion is less than neo-classical banana diffusion at all radii provided the field modulation at the plasma boundary is less than about 3.5%. The condition that the ion thermal diffusivity be everywhere less than the neo-classical banana diffusivity is somewhat more stringent, requiring the field modulation at the boundary to be less than about 2.5%.

With parameters typical of existing Tokamaks and a field ripple of 6%, the calculated ripple diffusion is comparable with the neo-classical toroidal diffusion, while the ripple contribution to ion thermal conductivity is less important. Resistivity measurements on T-3 suggest that the effective scattering frequency may be greater that the Coulomb collision frequency, perhaps due to turbulent fluctuations or impurities. Such an effect would decrease the ripple diffusion while increasing the toroidal contribution.

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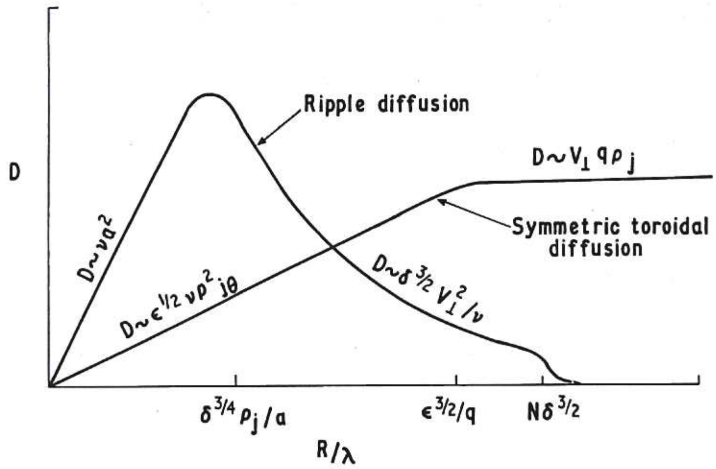

Fig. 1 Variation in the approximate ripple diffusion rate with collision frequency, compared with neoclassical diffusion in a symmetric system.

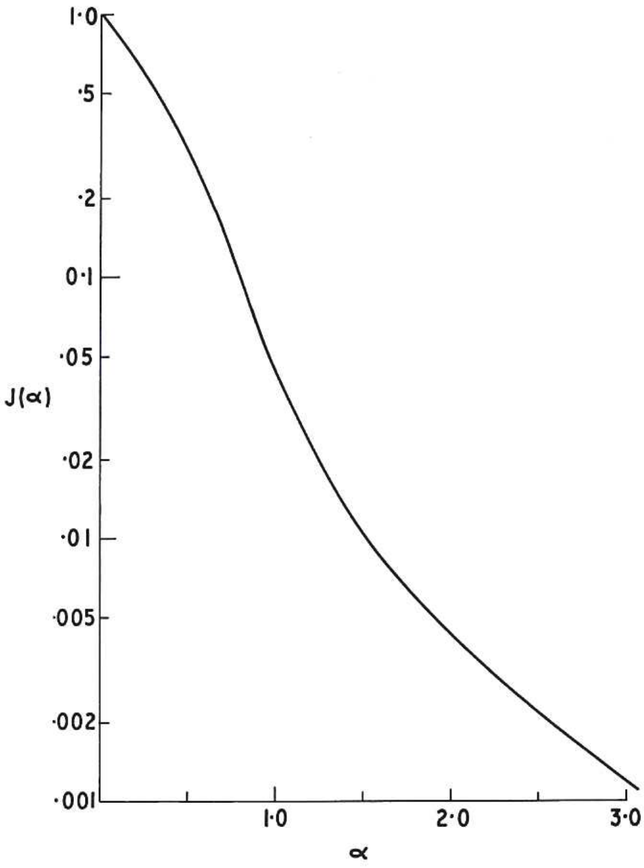

Fig. 2 $J(\alpha)$ factor resulting from reduction in ripple well depth by toroidal variation in field strength.

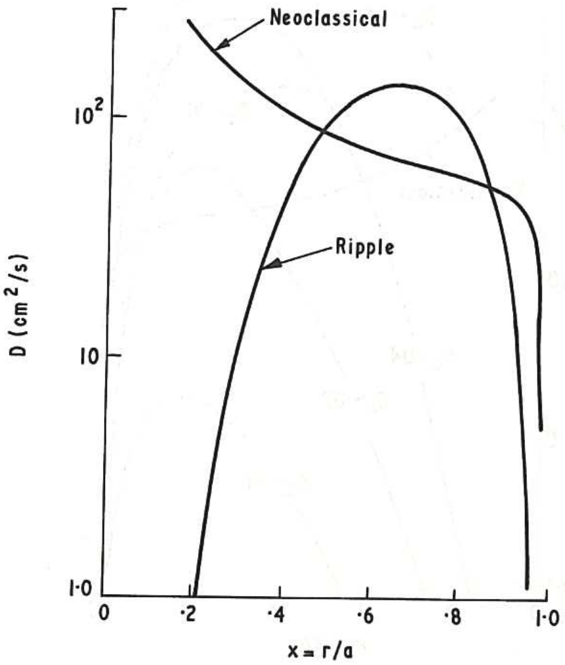

Fig. 3 Ripple and neoclassical diffusion coefficients vs. radius for parameters typical of existing Tokamaks.

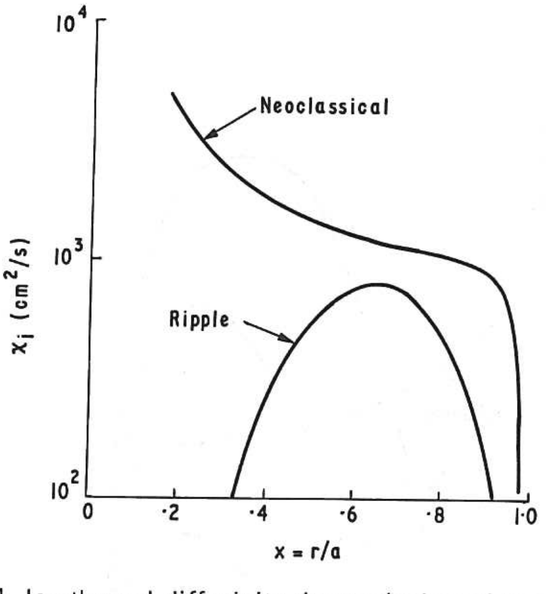

Fig. 4 Ion thermal diffusivity due to ripple and toroidal effects for parameters typical of existing Tokamaks.

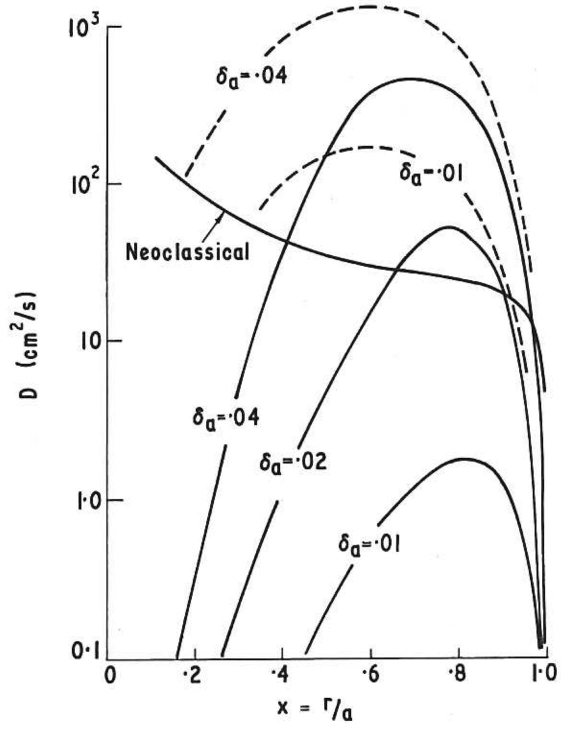

Fig. 5 Ripple and neoclassical diffusion coefficients for parameters typical of next generation Tokamaks. The field ripple at the plasma boundary is $\pm\delta_a B_0$. Dashed lines show prediction when reduction in ripple well depth by toroidal variation is neglected.

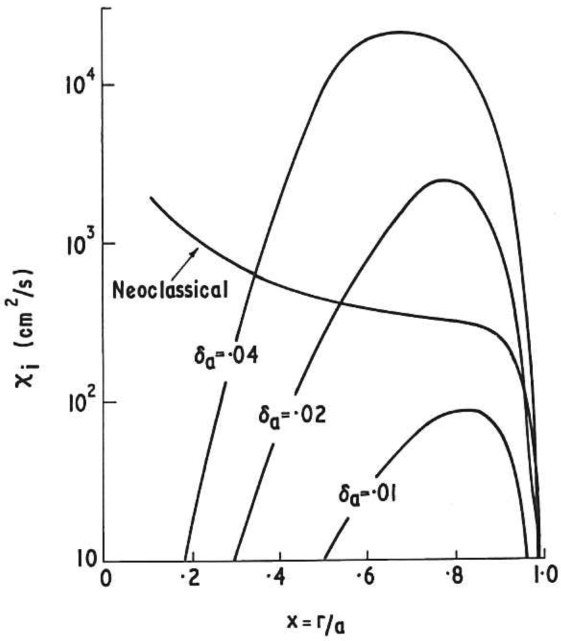

Fig. 6 Ion thermal diffusivity due to ripple and toroidal effects for parameters typical of next generation Tokamaks.