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CALCULATION OF TRITON CONFINEMENT AND BURN-UP IN TOKAMAKS

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Abstract

An analytical investigation is made of the confinement and subsequent burn-up of fusion produced tritons in a deuterium Tokamak plasma. Explicit approximations are obtained for the triton confinement factor, clearly displaying the scaling with physical parameters. The importance of pitch angle scattering losses during the triton slowing down is also estimated. A comparison with experiments and numerical calculations on the FT Tokamak slows good qualitative agreement.

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1. Introduction

The realization of a future DT Tokamak reactor will depend crucially on the confinement properties of the fusion produced alpha particles. The alphas must be confined long enough to deposit most of their energy in the plasma in order to sustain the plasma temperature. On the other hand the low energy alpha particles represent fusion ashes which would quench the reactor if they were allowed to accumulate in the plasma. Thus, ideally alpha particles should have an energy dependent confinement time which ensures good confinement at high energies and rapid loss at the thermal energies. Unfortunately, present theoretical understanding rather points to the opposit.

Although little direct experimental evidence exists on the confinement properties of fusion produced alpha particles, important indirect information on the containment of high energy charged fusion products has recently been obtained through burn-up studies [1-3]. In particular, in a deuterium discharge, 1 MeV tritons are produced by the reaction D(d,p)T with nearly equal probability as the 2.34 MeV neutrons produced by the reaction $D(d,n)^3He$. A fraction of the tritons may subsequently react further to produce 14.1 MeV neutrons by the reaction $D(t,n)^4He$. The ratio of the neutron fluxes at 14.1 MeV and 2.45 MeV depends on the reaction probability of the $D(t,n)^4He$ reaction process but also on the confinement of the tritons as they slow down from 1 MeV through the maximum of the $D(t,n)^4He$ cross section around 170 keV to thermal energies, cf Fig. 1.

Previous investigations[1-3] have assumed that the 1 MeV tritons can be divided into confined and unconfined particle populations and that the confined tritons slow down classically to thermal energies without suffering further loss. The cumulative probability of fusion for a confined triton during slowing down is shown in Fig. 2. Note the rapid rise in the energy interval 100-399 keV.

This implies that the (D,T)/(D,D) neutron emission ration, R, can be related to the confinement factor, f_c, corresponding to prompt losses of tritons by[3]

$$R = f_c \langle P_{DT} \rangle \tag{1}$$

where $\langle P_{DT} \rangle$ is the average probability of fusion for a confined slowing down triton.

In order to determine the prompt loss fraction of the tritons, numerical procedures, mostly based on orbit following techniques, have been used. While these are necessary in order to arrive at quantitatively correct results for realistic situations, it is also desirable to have access to simpler analytical estimates which yield a clearer physical insight as well as an explicit scaling of the losses with different parameters.

An approximation common to all of the numerical studies of the burn-up problem is the neglect of pitch angle scattering effects. In particular, the investigations[1,3] do not take into account the fact that particles may be lost by collisional pitch angle scattering into the loss region during slowing down. The pitch angle scattering operator, L_{PAS} in the Fokker Planck equation, which determines the evolution of the distribution function, f, of the tritons during slowing down is of the form[4]:

$$L_{PAS} \sim \frac{1}{E^{3/2}} \frac{\partial}{\partial \chi} (1-\chi^2) \frac{\partial f}{\partial \chi} \tag{2}$$

where E is the energy and $\chi = v_\parallel / v$ is the cosine of the pitch angle of the triton. The high energy of the triton tends to make the coefficient in front of the derivatives small, but the presence of a loss region in velocity space creates a steep gradient which could compensate the small coefficient and possibly lead to significant pitch angle scattering loss. The situation is aggravated by the fact that the birth energy of the triton (1 MeV) is much larger than the energy corresponding to the peak in the $D(t,n)^4He$ reaction cross section (170 KeV). This could imply that the tritium burn-up is sensitive to non prompt losses like pitch angle scattering (PAS) losses[1]. The purpose of the present work is to derive simple analytical estimates for the prompt as well as the PAS losses for the tritium burn-up problem and to assess their scaling with various physical parameters. A special application to burn-up studies on FT will also be made.

2. Prompt losses

An estimate of the prompt loss fraction of high energy charged fusion products can be based on either of two complementary assumptions:

(i) Trapped particles whose banana orbits intersect the wall are lost

To describe the corresponding loss region in velocity space we will use the model for the loss region as employed in Ref. [5] for its computational convenience, cf Fig. 3.

In this simplified representation of the particle losses, the loss region is characterized by three parameters; the energy, E_S, corresponding to the vortex of the loss region, the energy, E_u, corresponding to the outer limit of confinement for counter going particles, and the cosine of the pitch angle, χ_{min}, corresponding to the LHS of the wedge shaped part of the loss region. These parameters are determined by[5,6].

$$\chi^2_{min} = \frac{1+3r/a}{2(A+r/a)}$$

$$E_S \equiv \frac{1}{2} mv_s^2 = \frac{2}{M} \left[AZIP_s(r/a)\right]^2 \quad \text{(MeV)}$$

$$E_u \equiv \frac{1}{2} mv_u^2 = 2A\left[P_u(r/a\right]^2 E_S \qquad (3)$$

where r is the birth radius of the particle, a is the inverse aspect ratio, Z and M are the charge and mass number respectively of the particle, I is the total current in MA and $P_S(x)$ and $P_u(x)$ are determined by the current profile according to

$$P_S(x) = \left(\frac{2}{A}\right)^{1/2}\left[F(1)-F(x)\right]\left\{\left[1+\frac{x}{A}\right)(1+3x)\right]^{1/2} + \left[(1+\frac{1}{A})(3+x)\right]^{1/2}\right\}^{-1}$$

$$P_u(x) = \left\{\left[(1+\frac{x}{A})(1+3x)\right]^{1/2}+\left[(1+\frac{1}{A})(3+x)\right]^{1/2}\right\}\left\{2(1+x)\right\}^{-1} \qquad (4)$$

where F(x) is the normalized flux function. Assuming a current profile, J(r), of the form

$$J(r) \sim \left(1-\left(\frac{r}{a}\right)^n\right)^p \tag{5}$$

the flux function becomes

$$F(x) = \sum_{j=0}^{p} \frac{(-1)^j x^{nj+2}}{(nj+2)^2} \binom{p}{j} \left[\sum_{j=0}^{p} \frac{(-1)^j}{(nj+2)} \binom{p}{j}\right]^{-1} \tag{6}$$

We emphasize that whereas χ_{min} is independent of total current and current profile, E_S and E_u are strongly dependent on both.

From our simplified model for the loss region we easily infer the following prompt loss fraction, $\ell(r)$, for particles born isotropically in velocity space with energy, E_B, at radius r:

$$\ell(r/a) = \begin{cases} 0 & r \leq r_s \\ \frac{1}{\sqrt{8A}} \left(\frac{1+3\ r/a}{1+r/(aA)}\right)^{1/2} \left(1-\sqrt{\frac{E_S(r)}{E_B}}\right) & r_s \leq r \leq r_u \\ \frac{1}{2}\left[1-\left(\frac{E_S(r)}{E_B}\right)^{1/2} \frac{1}{\sqrt{2A}} \left(\frac{1+3\ r/A}{1+r/(aA)}\right)^{1/2}\right] & r_u \leq r \leq a \end{cases} \tag{7}$$

where r_s and r_u are defined by

$$E_S(r_s) = E_B$$

$$E_u(r_u) = E_B \tag{8}$$

In order to simplify the evaluation of the total loss fraction we approximate further as follows:

$$\left(\frac{1+3\ r/A}{1+r/(aA)}\right)^{1/2} \simeq 1+r/a$$

$$\left(\frac{E_S(r/a)}{E_B}\right)^{1/2} \simeq K_S(1-r/a)$$

$$\left(\frac{E_u(r/a)}{E_B}\right)^{1/2} \simeq K_u\ (1-r/a) \tag{9}$$

where

$$K_S = \left(\frac{A}{ME_B(\mathrm{MeV})}\right)^{1/2} \frac{2ZIF(1)}{1+\sqrt{3}(1+1/A)}$$

$$K_n = \left(\frac{2}{ME_B(\mathrm{MeV})}\right)^{1/2} AZIF(1) \tag{10}$$

Thus the local loss fraction can be approximated as

$$\ell(r/a) \simeq \begin{cases} 0 & r \leq r_s \\ \frac{1}{\sqrt{8A}}\left(1-K_S+r/a+K_S(r/a)^2\right) & r_s \leq r < r_u \\ \frac{1}{2}\left[1-\frac{K_S}{\sqrt{2A}}(1-r^2)\right] & r_u \leq r \leq a \end{cases} \tag{11}$$

where

$$r_s/a = 1-1/K_s$$

$$r_u/a = 1-1/K_u \tag{12}$$

Finally, assuming a birth profile, $n_B(r)$, for the fusion produced particles according to

$$n_B(r) \simeq n_B(0)(1-r^2/a^2)^m \tag{13}$$

we obtain the total loss fraction, L, as

$$L \equiv \int_o^a \ell(r/a)n_B(r)r\ dr \Big/ \int_o^a n_B(r)r\ dr =$$

$$= 2(m+1)\int_o^1 \ell(x)x(1-x^2)^m\ dx \tag{14}$$

Explicit analytical expressions for L can be obtained in different limits. In the present application we are particularly interested in the situation when $0 = K_S < 1 < K_u$ in which case

$$L = \frac{1}{2}\left[1-\left(\frac{r_u}{a}\right)^2\right]^{m+1} + \frac{2(m+1)}{\sqrt{8A}}\int_0^{r_u/a} x(1+x)(1-x^2)^m\, dx \qquad (15)$$

Note the particular limits

$$L = \begin{cases} \frac{1}{\sqrt{8A}}\left[1+2(m+1)\frac{(2m)!!}{(2m+3)!!}\right] & K_u \gg 1 \\ 0.5 & K_u < 1 \end{cases} \qquad (16)$$

(ii) <u>All banana trapped particles are lost</u>

Recent investigations[7,8] on the confinement properties of high energy charged fusion products in the presence of toroidal magnetic field ripple have shown that ripple trapping and stochastic banana diffusion lead to a rapid loss of all banana trapped particles. We emphasize that even for Tokamaks where the toroidal magnetic field ripple is not strong enough to create ripple wells over a significant part of the plasma cross section, stochastic banana diffusion alone could lead to rapid loss of fast particles on banana orbits.

To describe the loss region in this case we will use the following model: In the velocity range $v_\parallel \leq 0$ the loss region coincides with the loss region of Fig. 3 assuming $v_s = 0$. For $v_\parallel \geq 0$ all particles in the trapped velocity range $v_\parallel/v \leq (2r/aA)^{1/2}$ are assumed lost, cf Fig. 4

The total loss fraction in this case is obtained from eq. (15), adding all trapped cogoing particles. This yields

$$L = \frac{1}{2}\left[1-\left(\frac{r_u}{a}\right)^2\right]^{m+1} + \frac{1}{\sqrt{8A}}\left[H_m(r_u/a)+G_m\right] \qquad (17)$$

where for simplicity we have introduced the integrals

$$H_m(x) = 2(m+1) \int_0^x t(1+t)(1-t^2)^m \, dt$$

$$G_m = 8(m+1) \int_0^1 t^4(1-t^4)^m \, dt \qquad (18)$$

We emphasize the limits $r_u/a \simeq 1$ and $r_u = 0$ where

$$L \simeq \begin{cases} \frac{1}{\sqrt{8A}} \left[1+2(m+1) \frac{(2m)!!}{(2m+3)!!} + G_m\right] & r_u \simeq 1 \\ 0.5 + \frac{1}{\sqrt{8A}} G_m & r_u = 0 \end{cases} \qquad (19)$$

3. Pitch angle scattering losses

In order to estimate the PAS losses into the loss regions during slowing down and the subsequent effect on the burn-up ratio, we first make a short resumé of relevant results from Ref. [4]. Consider the loss region in velocity space caused by particles trapped in localized mirrors due to toroidal magnetic field ripple and drifting to the wall. A simple representation of this loss region is $\{(v_\parallel v_\perp);\ v_\parallel = 0,\ v_\perp \geq v_R\}$ where in the application of Ref. [4], $E_R \equiv \frac{1}{2} m v_R^2$ represents the critical energy at which the particle will be scattered out of the ripple mirror before reaching the wall. In the present case E_R will rather correspond to the vertex energy, E_S, or a characteristic energy associated with the peak of the fusion cross section.

The normalized PAS losses, P(v), into the loss region of Fig. 5 during slowing down can be written as

$$P(v) = \int_v^{v_B} p(v)dv \qquad (20)$$

where p(v)dv is the normalized number of particles lost in the velocity interval v to v+dv during slowing down. For p(v) we have[4]

$$p(v) = \frac{3}{4}\left(\frac{3\alpha}{2}\right)^{1/2} \frac{1}{v_c} \frac{(v_c/v)^4}{1+(v_c/v)^3} \left[\ell n \frac{1+v_c^3/v^3}{1+v_c^3/v_B^3}\right]^{-1/2} \tag{21}$$

where

$$\frac{1}{2} m v_c^2 = 14.8\ T_e M[Z]^{2/3}$$

$$\alpha = \frac{Z_{eff}}{2M[Z]} \tag{22}$$

We remind of the definitions of $Z_{eff} = (\Sigma\ n_i Z_i^2)/n_e$ and $[Z] = (\Sigma\ n_i Z_i^2/M_i)/n_e$ where i and e refer to background ions and electrons respectively.

The expression for p(v) given by eq. (21) is only valid for particle energies $E \geq E_*$ where[4]

$$E_* = E_c/\left[(1+v_c^3/v_B^3)\exp\left(\frac{3}{8\alpha}\right)-1\right]^{3/2} \tag{23}$$

In the present context E_* is lower than all relevant energies and eq. (21) can be used throughout.

The cumulative particle loss, P(v), can be obtained from eq. (21) as

$$P(v) \simeq \left[\frac{3\alpha}{8}\ \ell n \left(\frac{1+v_c^3/v^3}{1+v_c^3/v_B^3}\right)\right]^{1/2} \tag{24}$$

and since in the present range of energies $v_c^3 \ll v^3 \ll v_B^3$ we can approximate P(v) to read

$$P(v) \simeq 3\ Z_{eff}^{1/2}\ M^{1/4} \left(\frac{T_e}{E}\right)^{3/4} \tag{25}$$

In connection with eqs (21) and (25) we note that the PAS loss flow, p(v), increases with decreasing particle energy as a consequence of the increased PAS coefficient at lower energies, cf eq. 2. However, we emphasize that p(v) also becomes large at energies $E \lesssim E_B$ (p(v) has an integrable singularity at $v = v_B$) which reflects the influence of the steep pitch angle gradient of the distribution at the initial stage of the slowing down.

The finite extent of the loss region in the present application, cf Figs 3 and 4, introduces some modifications of the results given by eqs (21) and (25). Due to the factor $1-\chi^2$ in the PAS operator, eq. (2), the PAS loss flow through loss region boundary lines corresponding to constant pitch angle is decreased by a factor $(1-\chi^2)^{1/2}$, [9]. Since $\chi^2_{min} \ll 1$ and $2r/(aA) \ll 1$ we can neglect this correction for the trapping boundaries, but for $r > r_u$ no PAS losses will occur at the boundary line $\chi = -1$. For case (i) the RHS boundary line of the wedge shaped part of the loss region represents a more complicated problem, being a diffusion problem involving a moving boundary, [9]. For a situation with good confinement ($v_s \lesssim v_B$), the particles have to scatter a large angle in order to reach the loss region during slowing down, implying that the loss flow becomes small and can be neglected. However, for $v_s \ll v_B$, the boundary line can be approxi mated by $v_\parallel/v \approx 0$ and an unreduced PAS flow will enter the loss region from the left, cf [9].

Thus the PAS losses into the loss regions of Figs 3 and 4 can be written

$$P \approx 3\, h\, Z_{eff}^{1/2}\, M^{1/4} \left(\frac{T_e}{E}\right)^{3/4} \qquad (26)$$

where h represents a degradation factor which is determined by the particular geometry of the loss region. Furthermore, in order to evaluate the total scattering loss, an integration over the plasma cross section should be performed taking into account the changing form of the loss region with r and v. This becomes unnecessarily complicated for our present purpose and we will use simple estimates based on the arguments above when assessing the PAS losses for the particular applications concidered below.

As a qualitative check on the usefulness of eq. (26) we apply it to the case of alpha particle losses due to PAS into a loss region of type (i) as analyzed numerically in [10] and also in detail analytically in [9]. For a 3.5 MeV alpha particle in a plasma with $Z_{eff} = 1$, $T_e = 8$ KeV and assuming $h = 0.5$ we find $P \simeq 2\%$ in excellent agreement with the results of Refs [9,10].

4. Application to FT burn-up studies

The toroidal magnetic field ripple in the FT Tokamak is strong enough to cause ripple well formation over most of the plasma cross section. This implies significant trapped particle losses due to ripple enhanced diffusion of banana orbits, cf [7,8]. We will therefore use the loss region corresponding to case (ii), cf Fig. 4.

For 1 MeV tritons in FT (A=4.1) with a total current of 0.5 MA we obtain

$$K_u = \begin{cases} 1.7 & \text{peaked current profile } (F(1) = 1) \\ 0.8 & \text{flat current profile } (F(1) = 1/2) \end{cases}$$

which corresponds to $r_u/a = 0.4$ and $r_u/a = 0$ for peaked and flat current profiles respectively.

In FT two types of discharges can be distinguished: (a) wellbehaved discharges involving sawtooth- but little MHD-activity and (b) discharges characterized by strong MHD ($m = 2$, $n = 1$) activity[2,3]. For case (a) all characteristic profiles and in particular current and temperature profiles tend to be peaked whereas in case (b) the current profile and the temperature profiles are thought to be considerably flatter.

This can be made more quantitative by assuming the current profile to be linked to the q-value at the edge, q(a), according to $p = q(a)-1$, [7]. Furthermore, if the electron and temperature profiles are taken in the form $T_i \simeq T_e = T_e(0)(1-r^2/a^2)^s$, the assumed current-electron temperature relation $j \sim T_e^{3/2}$ implies $s = 2p/3$. Since the birth profile depends on the square of the deuteron density and the fourth power of the temperature (for $T_D \approx 1$ keV) the triton birth profile exponent is $m \approx 2 + 8p/3$ where we have assumed a parabolic ion density profile for both case (a) and case (b).

Thus for the different cases we have:

Case (a): Typical q-values are $q(a) \approx 3-4$ implying that $p \gtrsim 2$ and consequently $F(1) \approx 1$, $m \approx 7$. The characteristic parameter, K_u, is given by $K_u \approx 3.35$ I which yields $K_u = 1$ ($r_u = 0$) for $I \approx 0.3$ MA. The corresponding loss fraction is then $L \approx 0.50 + 0.18 = 0.68$ corresponding to a confined fraction of 0.32. As current increases the confinement improves and when r_u is larger than the radius corresponding to the peak of the triton production integral ($r\, n_B(r)$, i.e. $r_u > a/4$ or $I > 0.4$ MA we would expect a confinement factor of approximately 0.60. However, the onset of increased MHD-activity usually causes a switch-over to conditions characteristic of case (b).

Case (b): The increased extension of the $q = 1$ surface implies $q(a) \gtrsim 2$. Consequently $p \approx 1$, $F(1) = 3/4$, and $m \approx 5$. The characteristic parameter, K_u, is now given by $K_u \approx 1.5$ I which means that $r_u \approx 0$ for $I < 0.6$ MA, i.e. no significant improvement of confinement with current can be expected in the current range available for FT, once the discharge has developed into a pure case (b) situation. The loss fraction is now found to be $L \approx 0.50 + 0.20 \approx 0.70$ corresponding to a confined fraction of only 30%.

Combining the results of cases (a) and (b) we arrive at the following picture: As the current increases, confinement increases to reach a saturation value of approximately 60% in the current range 0.3 - 0.4 MA. If a transition to increased MHD activity occurs in this range, confinement drops to approximately 30% and then stays constant for further increase of current.

This scenario seems to be in qualitative agreement with experimental as well as numerical results for the burn-up ratio of tritons as given in Refs [1-3].

Estimation of pitch angle scattering losses

Since the pitch angle scattering loss is energy dependent we should really evaluate a weighted mean for $\sigma_{DT}v_T$. However, the peaking of the fusion cross section at energies slightly below 200 keV and the corresponding rapid rise of the cumulative probability of fusion in the energy range 200-300 keV, cf Figs 1-2, imply that a reasonable estimate of the degradation of the neutron emission due to PAS losses should be obtained from the following model: In the energy range $E_{PS} \leq E \leq 1$ MeV where $E_{PS} \approx 250$ keV we assume no DT reactions but only PAS losses. In the low energy range $E \leq E_{PS}$ all fusion reactions are assumed to take place with negligible PAS losses. This assumption yields the following estimate for the PAS loss that will affect the burn-up ratio in a 1 keV plasma

$$P \approx h \cdot 0.07$$

The degradation factor will vary between 0.5 and 1 but for small r_u it will be close to 0.5 (losses only through the RHS boundary of the loss region). Thus the PAS losses can be expected to be less than but of the order of 5% and the neglect of these losses in e.g. Refs [1-3] seems justified. Note, however, the strong scaling of P with Z_{eff} and T_e. For $Z_{eff} = 3$ and $T_e = 5$ keV, P increases to the order of 30%. Finally we note that if a minimum loss energy, E_{min}, existed for the loss region, it would replace E_{ps} in our estimates for P (provided $E_{min} > E_{ps}$).

Comments on finite Larmor radius effects

If the Larmor radius of the high energy charged particle is a finite fraction of the plasma minor radius two important effects should be included in the analysis, [1]:

(i) An effective limiter radius appears as a result of the fact that drift orbits passing within a gyroradius of the limiter is lost.

(ii) Since particles are born with random gyro phase, their guiding centre birth profile is roughly a gyroradius broader than the particle birth profile.

The first mechanism can be modelled by an effective limiter radius, $a_{eff} = a(1-\rho)$, where ρ is normalized Larmor radius ($\rho \approx 4.4 [ME(keV)]^{1/2}/(Za_{cm}B_{kG})$). This leads to two effects: (a) a scrape off of particles born within a gyroradius of the wall and (b) a widening of the loss region. For the parameters of FT the number of particles in the scrape off layer is small and most of them are considered lost anyway in the loss model of Fig. 4. The effect (b) can be included by using a_{eff} instead of a in the expressions defining χ_{min}, $E_s(r/a)$, and $E_u(r/a)$. Although the most important of these parameters is E_u, which determines r_u, a finite Larmor radius will not significantly increase the loss region for $\rho < 0.2$ (im the FT Tokamak $\rho = 0.18$ at 60 kG).

The effect of the broadening of the birth profile according to (ii) is more difficult to determine quantitatively, but for $\rho < 0.2$ we cannot expect but a moderate improvement of confinement with decreasing ρ.

Thus we conclude that changing the toroidal magnetic field should have little direct effect on the particle loss and the subsequent burn-up ratio. On the other hand, the toroidal magnetic field can indirectly determine the burn-up ratio by affecting either the ripple enhanced banana diffusion or the degree of MHD activity. Since the ripple on FT is strong enough (3% at the edge) to satisfy the criterion for ripple well formation in the entire plasma cross section, a change in magnetic field should not trigger a transition between loss region types (ii) to (i), cf Figs 3 and 4. Thus the most likely explanation of a large change in burn-up ratio for a moderate change in toroidal magnetic field strength seems to be the relation between toroidal magnetic field strength and MHD activity with its subsequent strong effects on burn-up ratio through profile effects.

Conclusions

An analytical model has been developed to predict the confinement properties of high energy charged fusion products in a Tokamak plasma where losses are due to orbit effects and collisional pitch angle scattering into the corresponding loss region in velocity space. A special application is made to the burn-up studies of fusion produced tritons in the FT Tokamak. It is shown that for characteristic FT parameters operation with and without MHD activity should lead to significant changes in the triton confinement. In particular, the analytical predictions are in qualitative agreement with the experimentally observed sudden drop in burn-up ratio when the increasing current triggers significant MHD activity.

The main reasons for the deterioration of triton confinement is the flat current and temperature profiles characteristic of discharges with significant MHD activity.

A flat temperature profile leads to a broadening of the triton birth profile which increases the losses as compared to the case of a peaked birth profile. Furthermore, a flat current profile greatly enhances the local loss region in velocity space as compared to the case of a peaked current profile.

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Figure Captions

Fig. 1. Fusion reaction cross section for the D(t,n)^{4}He process. (From Strachans Fig. 1 of Ref. [1].)

Fig. 2. Cumulative probability of fusion for a confined triton. (From Haegi & Bittoni, Ref. 3).)

Fig. 3. Simplified model for loss region in case (i).

Fig. 4. Simplified model for loss region in case (ii).

Fig. 5. Model loss region used in Ref. [4] for the evaluation of alpha particle ripple losses in a Tokamak reactor.

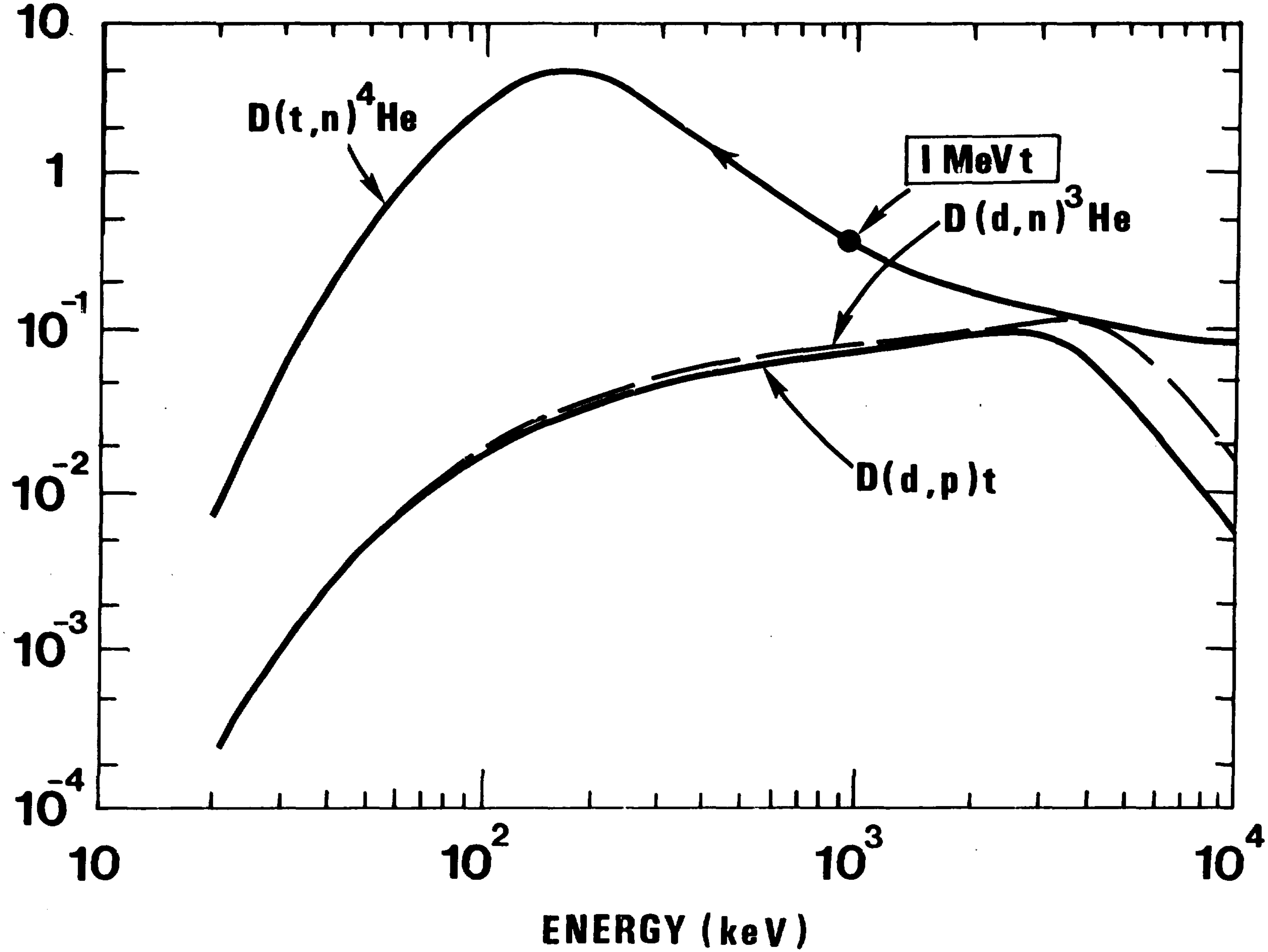
D(t,n)^{4}He
1 MeV t
D(d,n)^{3}He
D(d,p)t
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10
10^2
10^3
10^4
ENERGY (keV)

Fig. 1

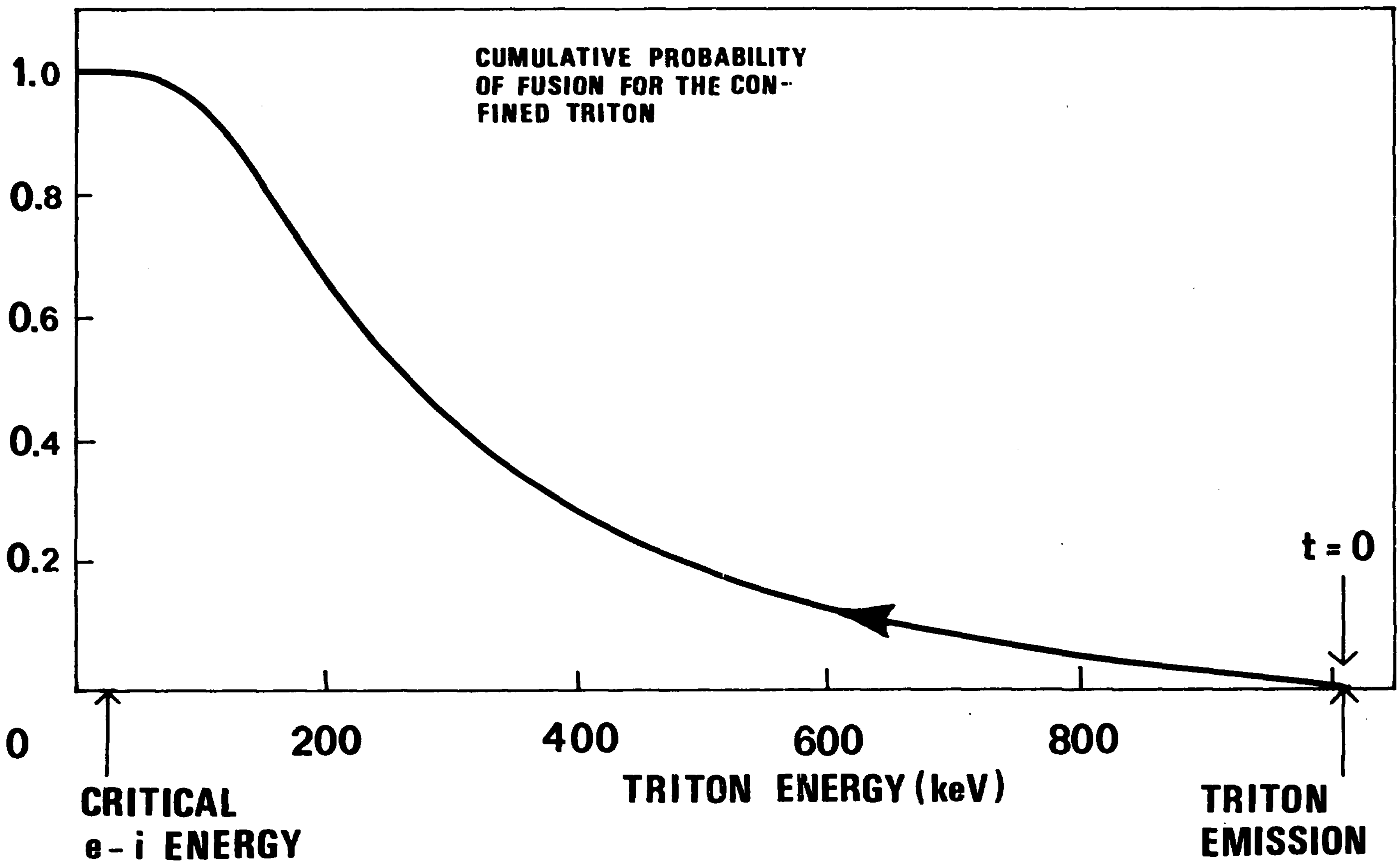
CUMULATIVE PROBABILITY OF FUSION FOR THE CON- FINED TRITON
1.0
0.8
0.6
0.4
0.2
0
200
400
600
800
t = 0
TRITON ENERGY (keV)
CRITICAL e - i ENERGY
TRITON EMISSION

Fig. 2

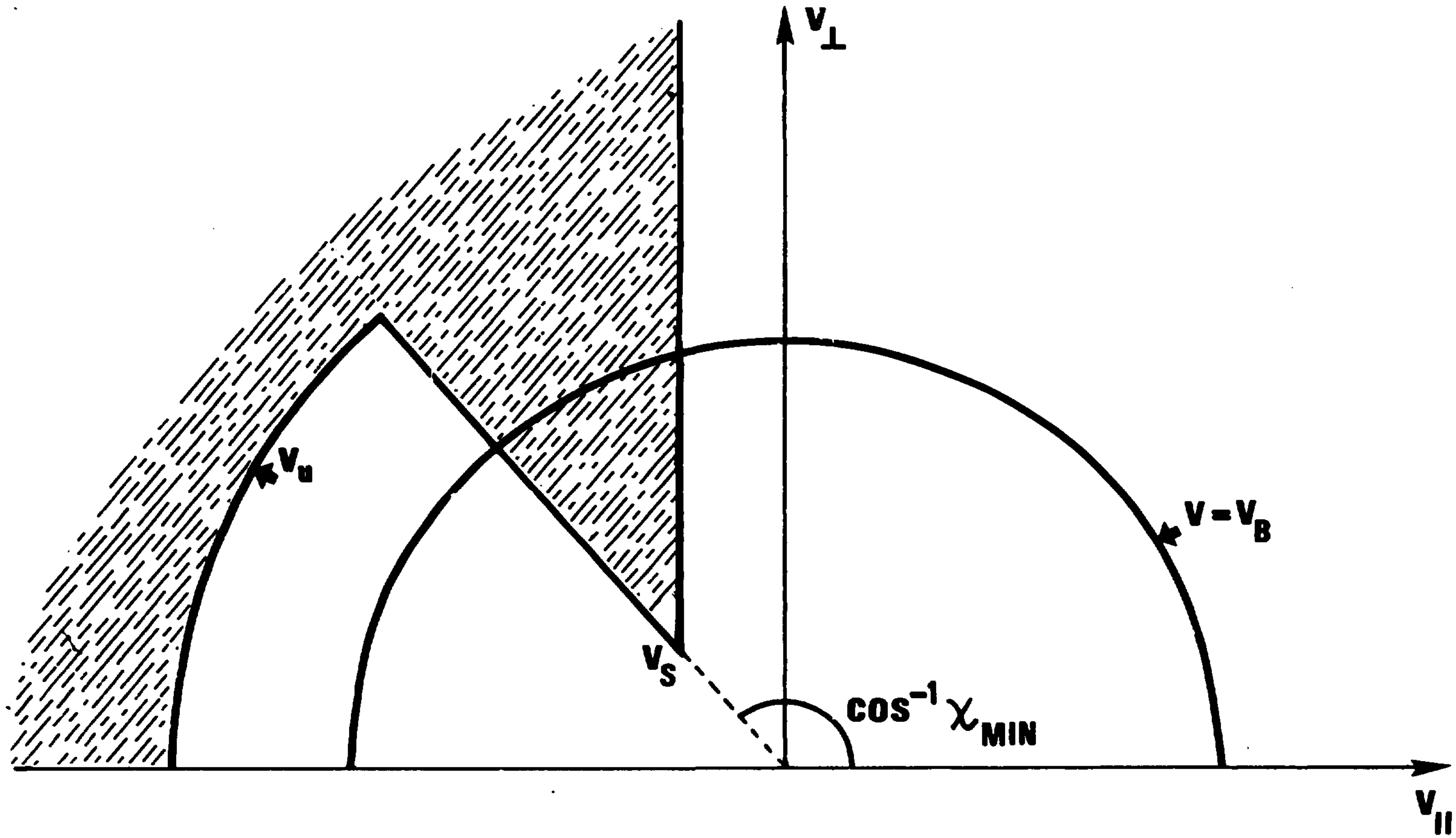

Fig. 3

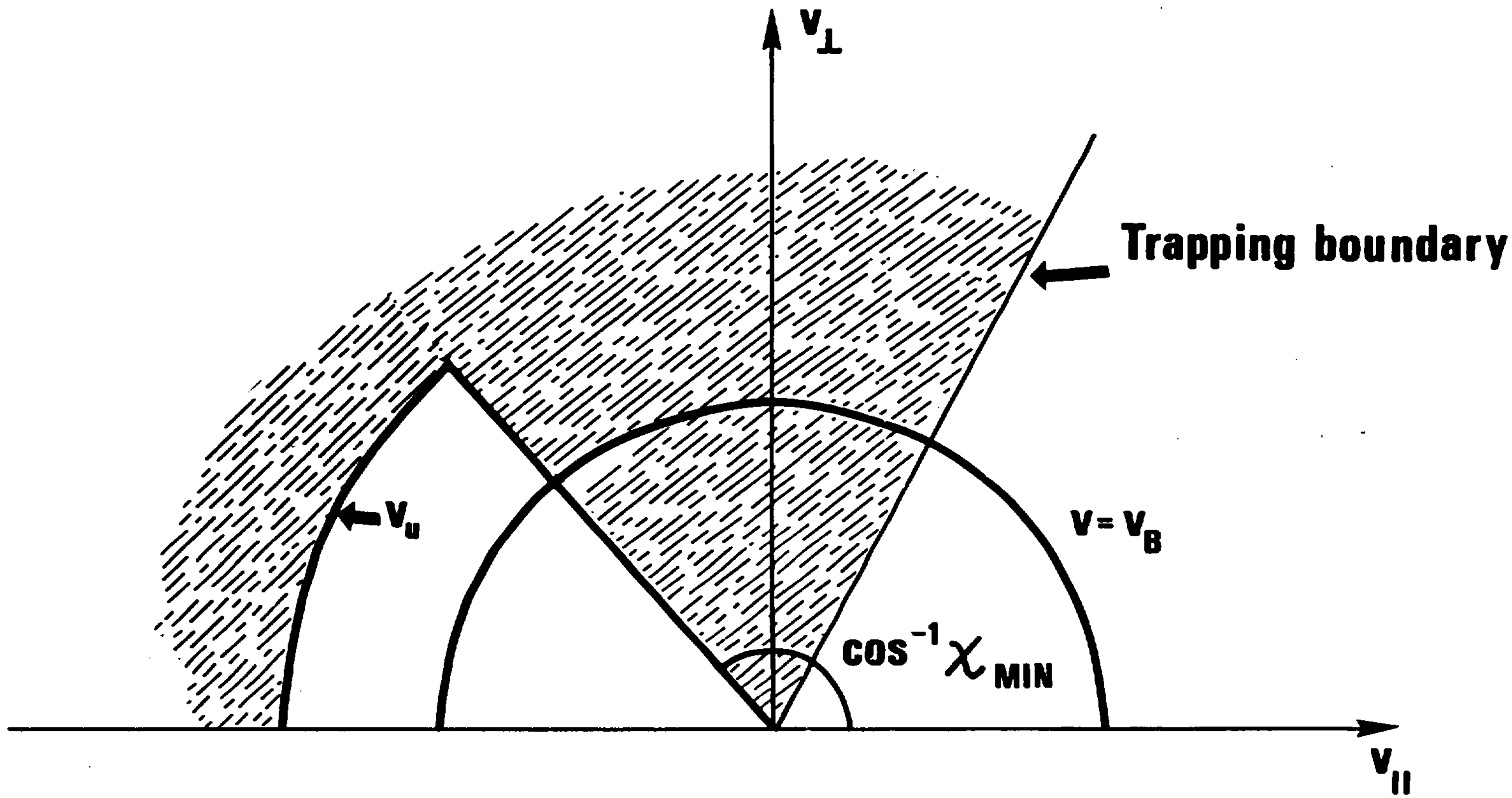

Fig. 4

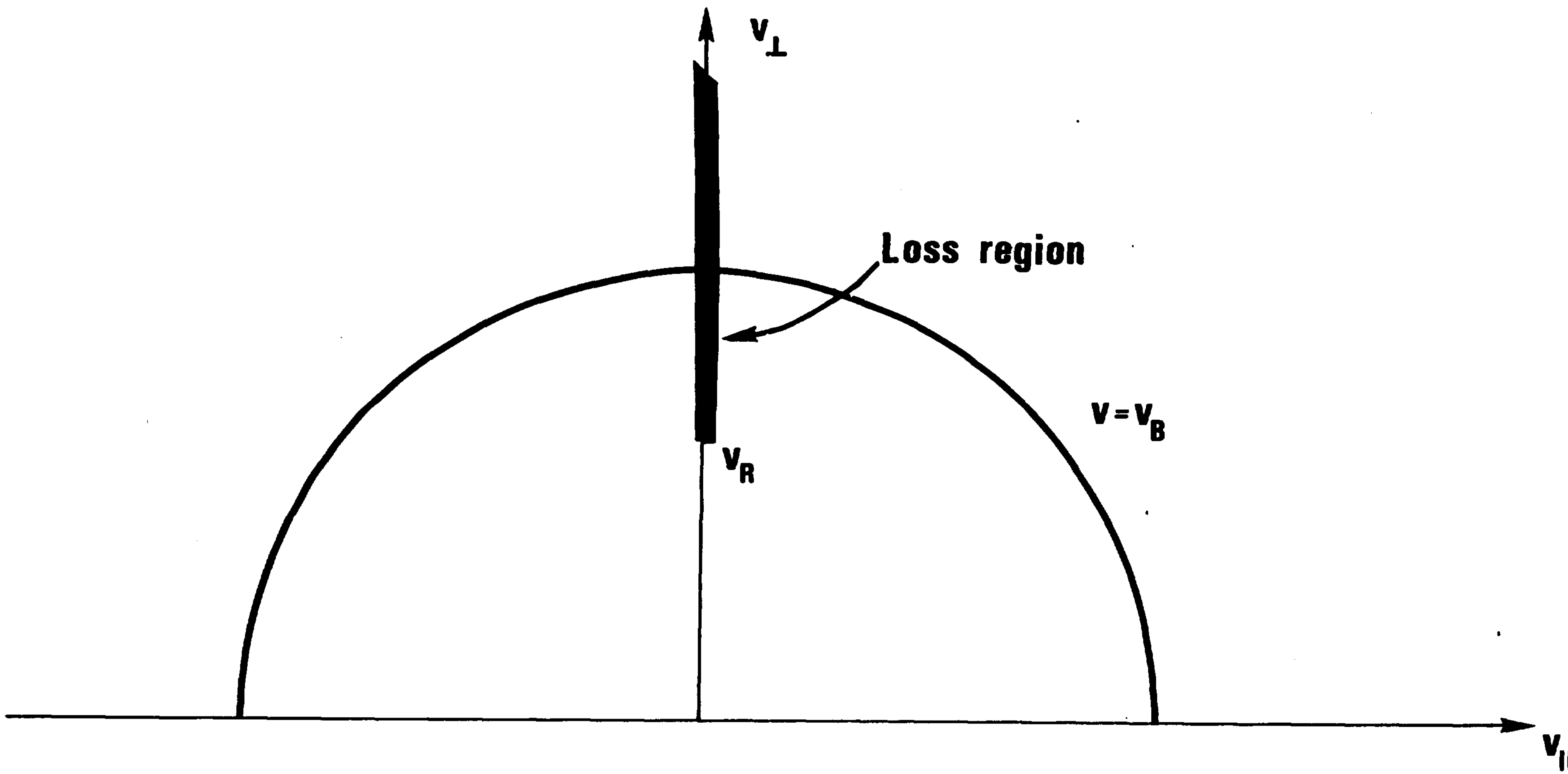

Fig. 5