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by
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Abstract

Plasma engineering studies at the Fusion Studies Laboratory of the University of Illinois, Urbana, IL are described that deal with: fusion-product transport in plasmas and associated effects in tokamaks, neutral-beam injection and plasma build-up in mirrors, and studies of aspects of alternate confinement concepts including field-reversed mirrors, field-reversed pinches, and twin-beam mirrors.

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I. Introduction

As indicated in Fig. 1 the general objective of this project is the study of plasma engineering aspects of fusion reactors including fusion-product transport and wall bombardment, impurity control, neutral-beam injection and plasma build-up, and alternate confinement concepts.

Important achievements during the present contract period include:

Fusion-product transport and effects

- first calculation of alpha-particle heating profiles for tokamaks that include both detailed orbits and orbit drift during slowing down
- first calculation of angular dependence of alpha particle bombardment of tokamak first wall, both with and without ripple
- proposal and preliminary design calculations for an alpha particle measurement using detectors on the wall of an experimental device such as PLT
- first detailed calculation of radial electric-field caused by alpha particle losses and subsequent plasma rotation
- identification of two new invariants, k and m to describe alpha slowing in the region where electron drag dominates
- development of unique envelope method to describe fusion-product orbits and their drift during slowing down
- preliminary studies of the effect of variations in the spatial distribution of alpha thermalization on thermal diffusion and subsequent alpha "ash" build-up in tokamaks
- identification of potential EM cyclotron wave instabilities driven by superthermal alphas

Mirrors and alternate confinement concepts

- first application of a simplified three-dimensional representation of field-reversed mirror fields using an analogy with Hill's vortex to classify orbits and diffusion in the field-reversed mirror
- first 2-D Fokker Planck study of multiple-energy injection into mirror devices
- first global treatment of the field-reversed mirror that includes energy groups and a self-consistent treatment of diamagnetic currents
- first treatment of field-reversed pinch burn that employs a helical current model which allows β - θ stability analysis

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Figure 1. Scope of Plasma Engineering Studies in the Fusion Studies Laboratory.

II. Publications

During this period 45 reports were published. For convenience, these reports as well as a complete listing of earlier publications are included as *Appendix A*. (Subsequent C00-2218 numbers indicated in the text refer to reports listed in Appendix A)

Included among these publications are 2 Ph.D. Theses (P. Meka, Ph.D., Nuclear Engineering; T. Petrie, Ph.D., Physics) and two MS Theses (H. Stimpson, M.S., Nuclear Engineering; H. Yuen, M.S., Computer Science).

Since progress during this period is well documented by these reports, the present discussion will simply review some highlights. The interested reader can then obtain further details from the reports referenced.

III. Fusion-Product Transport Studies

As research moves towards an era of *fusion-grade plasmas*, a key question is whether or not fusion products (here we restrict our attention to 3.5-MeV alpha particles from D-T reactions) introduce new or unexpected effects in the fusing plasma or its container (i.e., the first-wall.) "Classical effects" indicated in Fig. 2 have received most of our attention to date although, as indicated in Fig. 3, some attention has also been devoted to anomalous effects related to possible instabilities.

An overview of this work was presented in C00-2218-72, prepared for the 1977 *IEEE International Conference on Plasma Sciences* and reproduced below for the convenience of the reader.

- PLASMA HEATING
- ROTATION
- IMPURITY BUILD-UP
- WALL-LOADING

Figure 2. Important Effects Due to High Energy Fusion-Products

- ION-ACOUSTIC WAVE
- ALFVEN WAVE
- E-M CYCLOTRON WAVE
- TRAPPED ION MODE

Figure 3. Types of Instabilities Studied

Effect of Fusion-Product Transport and Losses. G. H. MILEY, T. PETRIE, L. HIVELY, and M-Y WANG, Fusion Studies Lab., U. of Ill., Urbana, Ill.--The fate of high-energy fusion-products generated in fusion plasmas is a crucial question for reactor development for several reasons. First, heating of the plasma must be efficient for ignited operation while unwanted instabilities must be prevented. Second, the first-wall design must account for bombardment and possible blister-type erosion due to these products escaping the plasma. Third, the thermalization profile of products is important relative to their eventual build-up (as an impurity) in the plasma. Fourth, the products may be used, e.g., for temperature control or for diagnostic purposes.

Our studies of these effects have focused on the development of techniques to treat three distinct problems: a) rapid computation of product-orbits during thermalization, b) methods to evaluate the spatial dependence of wall-loadings, and c) evaluation of potential microinstabilities plus gross MHD effects such as plasma rotation. The thermalization treatment is a key feature.⁽¹⁾ To circumvent the problem of following many orbits, a phase-group trajectory method is employed along with a weighted energy-loss model. Calculations for representative TFTR- and reactor-type plasmas indicate that the alpha heating profile is considerably flattened compared to the "in-situ" approximation used in most global models. The thermalization profile is even flatter, being more sensitive to transport of lower energy alphas (<1 MeV).

The wall-loading profiles capitalize on the identification of classes of orbits and a convenient analytic formulation of the orbit equation.^(1,2) Results have been obtained for cases ranging from TFTR-like plasmas to reactors. All cases show a peaked profile in the poloidal direction superimposed on a bumpy profile in the toroidal direction due to ripple effects. Localized effects such as blistering can be 5X or more above the average, posing a severe design limitation.

Calculations of the angular dependence of wall bombardment have also been performed. This is being done for experiments now in preparation at the PLT which will use wall detectors to measure bombardment.^(3,4)

One consequence of alpha losses is the generation of electric fields due to the relatively small cross-field mobility of electrons. The present treatment permits a self-consistent treatment of the radial field and evaluates the resultant plasma rotation.⁽⁵⁾ Principal damping forces include ion-neutral collisions, charge-exchange, and angular momentum diffusion. The latter dominates near the plasma center whereas charge-exchange is a key factor at the edge. Toroidal rotation generally dominates over any poloidal rotation. Again, results have been evaluated for both TFTR and reactor-like plasmas. In the latter rotation speeds approaching thermal speeds are predicted. While this is not expected to cause disruptive instabilities, the effect cannot be ignored and may be a useful diagnostic.

- [1] T. Petrie and G. H. Miley, "New Techniques for Studying Some Effects of Suprathermal Alpha Particles," ANS Mathematics and Computation Division Topical Meeting, Tucson, Arizona (March 1977). To be published, Nuclear Sci. and Eng. [2] L. Hively and G. H. Miley, Trans. Am. Nucl. Soc., 24, 58 (Nov. 1976). [3] L. Hively and G. H. Miley, "Comments About Proposed D-³He Experiments in TFTR," Report C00-2218-40, U. of Ill. (Oct. 1975). [4] H. Hindel, Princeton Plasma Physics Laboratory, Private communication, Dec. 1976. [5] T. Petrie and G. H. Miley, "Plasma Rotations Induced by 3.5-MeV Alpha-Particle Losses," Trans. Am. Nuc. Soc. (June 1977).

1) New Techniques for Studying Alpha Transport in Tokamaks

MeV alpha-particle transport in tokamaks is complicated by the large orbits involved. The resulting deviation from flux surfaces becomes too large to permit the conventional expansion techniques employed in diffusion theory. Consequently, a key to the analysis of alpha-particle effects is the development of new techniques to treat the alpha orbits and their drift during slowing down. Much of our work in this area employs a unique orbit drift model developed by T. Petrie and described in COO-2218-501, which is to be published in *Nuclear Science and Engineering*. To indicate the flavor of this approach, the abstract is reproduced below.

Phase-space grouping techniques have been applied to two distinct problems in fusion-product physics: (1) slowing-down drift motion of highly-energetic alpha particles in a symmetric toroidal field, and (2) first-wall loading by 3.52-MeV alphas resulting from magnetic ripple. In the former, a weighted energy-loss approximation method permits the evolving orbits to be determined for any representative phase-space group. This enables rapid computation of several important suprathermal effects in a tokamak plasma. For example, code SYMALF, which embodies this idea, is applied to plasma heating and alpha thermalization source problems. In the ripple field case, a probabilistic density function is employed to determine drift losses associated with ripple-trapped, 3.52-MeV alphas. When used to determine 3.52-MeV alpha wall-loadings, code RIPALF, which is based on this probability function, predicts the position of local "hot spots" along the first wall.

Important results from this work include: heating profiles, thermalization profiles, and spatial variation of the slowing-down distribution. Examples for a TFTR plasma are discussed in the section below extracted from T. Petrie's thesis (COO-2218-83).

Figure 1,* which assumes parabolic profiles in both temperature and density, shows energy deposition contributed by D-T produced alpha particles with energies above 500 keV. The

*Here and in future reproductions of (or extractions from) COO-2218 reports, the original figure numbers in the reports are retained. This should not be confusing since they are well-separated from consecutively numbered figures in the body of this progress report.

differences between the "in situ" results (solid line) and the drift model SYMALF's predictions (dashed line) are mainly attributed to first bounce losses not included in the "in situ" slowing-down model. When the "in situ" results are multiplied by the fraction not lost during the first orbit (the MIS model) results compare well with SYMALF, except for discrepancies of 50%-60% in the outer 1/5 of the plasma. More precise calculations such as afforded by SYMALF are necessary in some special cases, however. For example significant differences occur in Fig. 2 where the plasma density increases toward the outer edge of the plasma, representing neutral-gas blanket design. In this case, neither the "in situ" or MIS approaches are consistent with the SYMALF predictions.

Figure 3 shows the thermalization profile (at ~500 keV) for alphas assuming a parabolic density and temperature distribution. The shape of the SYMALF curve is noticeably different from MIS near the origin. This results from drifting during slowing down.

Figure 4 demonstrates how this energy-loss drift depleted the outer regions of the plasma of the lower energy alpha particles. The number of suprathermal alphas in each 600 keV energy segment decreases as the energy decreases for the $\hat{r} = .96$ case ($\hat{r}$ is the normalized minor radius). Since the distribution function will also display such behavior, this suggests a possible driving mechanism for microinstabilities.

Figure 1. Heating Profiles Calculated For TFTR (in situ approximation: solid line; SYMALF: dashed line)

Figure 2. Heating Profiles Calculated For TFTR with a Gas Blanket (SYMALF: dashed line; "in situ" model: dashed line; MIS model: dotted solid line)

Figure 3. Thermalization Profile Corresponding to Fig. 2.

Figure 4. Alpha-Energy Distribution vs Position in TFTR.

Several important new contributions to the analysis of alpha slowing were recently reported in the thesis of P. Meka (COO-2218-84). An abstract of this work follows:

An explicit expression, $\cos\theta = (R_0/r)[(\mu B_0/2) - 1 + \text{SQRT}((\mu B_0/2)^2 + ((P_\phi + (e/c)\Psi(r))^2/2mE_0^2)] = F(r)$, that describes the guiding-center motion of a high-energy charged particle in a lossless, axisymmetric, low-beta ($\beta \leq 0.1$) tokamak has been derived. The above expression is valid in any type of toroidal and poloidal field configurations as long as the poloidal flux surfaces, specified by $\Psi(r)$, are circular. A similar explicit expression is obtained for fields having a vertical stabilizing component, B_v .

In medium-beta tokamaks ($0.1 \leq \beta \leq 0.3$) such as FCTs, the Ψ surfaces are no longer circular. Choosing another orthogonal coordinate system (Ψ, χ, ϕ) instead of (r, θ, ϕ) , a similar explicit orbit equation, $B_\phi = B_\phi(\Psi)$, is derived to describe the guiding-center motion of fusion-products in medium beta tokamaks.

The explicitness property of the orbit equation is used to an advantage to derive expressions for first-orbit effects including differential loss-fractions and differential-total wall-loading profiles. Instead of following the normal practice of labelling the FP orbit with the pitch-angle ψ_p at birth, a different parameter, $\lambda \equiv (1 - \cos\psi_p)/2$, normalized to 1 for the entire range of ψ_p , is used. The difference of λ s between any two

curves, $(\lambda_2 - \lambda_1)$, automatically gives the fraction of the particles born at the intersection of the curves and which are moving in the region enclosed between the curves. Thus an order of magnitude estimate of the loss fraction can be obtained directly from these orbit plots.

This study of slowing-down effects of the fusion-products (FP) in the background plasma has provided important new information and techniques to handle FP slowing down. The adiabatic invariants μ , P_ϕ and E can no longer be assumed to remain constant when slowing down is included. The equation of change of μ , given by $(1/\mu)(d\mu/dt) = (1/E)(dE_C/dt)$ is derived assuming that the energy loss rate, (dE_C/dt) , takes place predominantly through electron drag with resultant negligible pitch-angle scattering (valid for most of the energy range of the fusion-products). Similarly the equation of change of P_ϕ , given by $E \cdot (dP_\phi/dt) = (P_\phi + (e/c)\Psi) \cdot (dE_C/dt)$, is derived.

Using the equations of change of μ and P_ϕ , special limiting cases of interest are studied. New invariants that are useful for the study of the transport of high-energy fusion-products in plasmas are presented. An important case of interest is when the ratio of the rate of change of energy due to collisions, (dE_C/dt) or $\dot{E}_C$, to the total rate of change of energy, $\dot{E}$, is a constant $f \equiv \dot{E}_C/\dot{E}$. The total rate of change of energy $\dot{E}$ is the sum of the rates of change of energy due to collisions $\dot{E}_C$ and that due to induction $\dot{E}_I$, or $\dot{E} = \dot{E}_C + \dot{E}_I$. Then it is found that μ and P_ϕ change with energy such that $\kappa(\text{KAPPA}) \equiv \mu/E^f = \text{constant}$ and $\mathfrak{M}(\text{AMMA}) \equiv (P_\phi - f(e/2c) \cdot E^{f/2} \int_{E_0}^E \Psi E^{-1-f/2} \cdot dE)^2/E^f = \text{constant}$. Invariants KAPPA, κ , and $\mathfrak{M}$

(AMMA) tend to $\mu = \text{const}$ and $P_\phi = \text{const}$ if $\dot{E}_C = 0$ or $f = 0$; and

$\mu/E = \text{constant}$ and $(P - (e/2c)E^{1/2} \int_{E_0}^E \Psi^{-3/2} dE)^2/E = \text{const}$ if $f = 1$.

The five variable problem of FP motion with slowing down is reduced to an ordinary integro-differential equation using the banana-orbit equation, drift-velocity equations and the invariants κ and $\mathfrak{M}$. Alternate approximate methods of solution are also developed. One, the Generalized Envelope (G.E.M.) Method, shows that the motion of an FP with slowing down can be studied to good accuracy by the solution of two simultaneous first-order ordinary differential equations. It has been shown that the two simultaneous differential equations can be reduced to one ordinary differential equation, thus demonstrating that only one ordinary first-order differential equation is required to study the motion of an FP with slowing down. Since the net drift velocities of the orbit are small, integration of these equations is fairly simple and rapid.

A numerical code, TRAKEM, that follows the FP by integrating the drift equations has confirmed the accuracy of the various new equations derived and the new methods developed.

2. Fusion-Product Bombardment of the First Wall

Alphas escaping the plasma that bombard the first wall can cause severe problems due to impurities that are released back into the plasma as well as wall erosion via blistering. Detailed calculations of this phenomena are reported in COO-2218-506, to be published in *Nuclear Fusion*. For convenience, a brief summary of some of this work is reproduced below from COO-2218-76P, published in *Trans. Am. Nuclear Soc.*, 24, 58 (1976).

1. Fusion-Product Bombardment of a Tokamak First Wall, L. M. Hively, G. H. Miley (U of Ill)

High-energy alpha particle bombardment of the first wall of a fusion reactor results in sputtering and blistering phenomena that may seriously contaminate the plasma and severely limit the wall lifetime. Evaluation of the wall-loading profile in a tokamak is complicated, however, by the banana-like orbits of the alphas. Consequently, a highly peaked loading occurs as a function of poloidal angle. The purpose of this work is to provide an accurate evaluation of this effect as an extension of previous work by Tenny¹ and McAlees² who concentrated on gross loss fractions.

Fig. 1. 3.52-MeV alpha flux on the first wall of selected tokamak reactors.

The wall loss model assumes a low- β axisymmetric tokamak operating in the collisionless regime. An exact analytical expression for the neoclassical guiding-center motion of the particle (mass, m ; charge, e ; energy, E ; magnetic moment, μ ; longitudinal adiabatic invariant, J) has been derived by Meka³:

$$\theta = \arccos \left(\frac{R_0}{r} \left\{ \frac{\mu B_0 + [\mu^2 B_0^2 + 2mE(J + F)^2]^{1/2}}{2E} - 1 \right\} \right) \quad (1)$$

for a major toroidal radius, R_0 , and toroidal field at R_0 , B_0 . The variable, $f = f(r)$, arises from integration over an arbitrary current density $j = \psi j(r)$.

$$f = \frac{4\pi e}{mc^2} \int_0^r \frac{dr'}{r'} \int_0^{r'} r'' dr'' j(r'') \quad (2)$$

We have solved Eq. (1) analytically, in a more general form than Rome et al.,⁴ to obtain the pitch angle, ϕ , corresponding to an orbit which begins anywhere in the plasma and intersects the wall at any point. We have also obtained a general form for the value of ϕ corresponding to stagnation orbits, which can occur for both $R < R_0$ and $R > R_0$. Study of the orbits has also shown that particles born near the inner (outer) plasma edge [$R < R_0$ ($R > R_0$)], can have minimum (maximum) loss angle, $\phi = 0$ ($\phi = 180$ deg). The wall loading from a given birth point is calculated for wall segments between wall-orbit intersections corresponding to $\phi_{\min}$ and $\phi_{\max}$. Finally, the loading profile is obtained by integrating over the plasma volume.

All the resulting losses are either to the upper- or lower-half-plane of the device, depending on the direction of the toroidal magnetic field. Examples of the loading profiles are shown in Fig. 1, for 3.52-MeV α losses from the TFTR weak compression plasma, the JET circular plasma, ANL-EPRI, and UWMKI. While alpha fluxes are not excessively large for these cases, blistering in the peak-flux areas may pose problems. We also conclude that the sensitivity of these loading profiles to plasma conditions may be a useful diagnostic for inferring $j(r)$, $n_i(r)$, and $T_i(r)$.

1. F. H. TENNY, MATT-1132, Princeton Plasma Physics Lab. (1975).
2. D. G. McALEES, ORNL-TM-4661, Oak Ridge National Lab. (Nov. 1974).
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In later generation reactors, ripple-trapping of alphas is expected to contribute a major fraction of the wall bombardment. The engineering and economic "trade-off" between maintenance costs associated with wall damage from the bombardment vs the added cost and complexity of adding toroidal magnets to reduce the ripple has been considered by G. Gerdin. Results from COO-2218-75 (*Trans. ANS*, 24, 53, 1976) are presented below.

Optimization of Magnet Coil Radius for a Tokamak Reactor

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Fusion α particles trapped in the wells of the toroidal magnetic field can escape the plasma and bombard the first wall in localized spots. The enhanced wall bombardment could cause increased first wall replacement frequency. All this can be alleviated by reducing the magnitude of the ripple by increasing the radius and or number (r_m and N) of the magnetic field coils. In this paper the wall bombardment by fusion α 's lost through TF ripple and the increased first wall replacement costs are calculated through an arbitrary parameter c : the ratio of α to neutron damage coefficients (each: per incident particle per unit area) for a given first wall material. Experimental data on c is fragmentary¹ at best so by treating it as an arbitrary parameter one can find the range of c necessary for the α damage to begin to affect the first wall replacement rate. Hence, the first wall replacement cost and magnet costs are both functions of the magnet radius, r_m , and an optimum magnet coil radius is found.

The toroidal magnetic field and the ripple coefficient are defined and approximated by²

$$B = B_0 [1 - r/R_0 \cos\theta - \epsilon(r, \theta) \cos N\phi] \quad (1)$$

$$\epsilon(r, \theta) = \epsilon(a, 0) \left(\frac{r}{a}\right)^{N/4} \exp(-\theta^2)$$

and

$$\epsilon(a, 0) = \frac{0.25}{\left(\frac{N}{12}\right)^3 \left(\frac{2r_m + r_c - R_0 - a}{3.2}\right)^{2.5}}$$

where r_c is the radius of the transformer core, N is the number of magnet coils, ϵ is the ripple coefficient and the rest of the notation is standard. The fraction trapped

$f_T(r, \theta)$, is $(2\epsilon)^{1/2}$ and the cosine of the loss cone angle, ξ_L , is $(2\epsilon)^{1/2}$. The pitch angle diffusion into this loss cone is taken to be gaussian³ and the root mean square deviation of the cosine of the pitch angle, $\langle \Delta^2 \xi(\bar{E}) \rangle^{1/2}$, for a particle slowing down from energy E_0 to energy $\bar{E}$ is given by:

$$\langle \Delta^2 \xi(\bar{E}) \rangle^{1/2} = \frac{(kT(E_0 - \bar{E}))^{1/2}}{2^{1/2} \bar{E}} \quad (2)$$

where $\bar{E}$ is the lowest energy at which an α may escape before experiencing a collision.

The major assumptions are that the α 's are confined to a flux surface until they scatter into the ripple loss cone, that the diffusion is isotropic in velocity space and the α 's interact with the background plasma only. The first assumption appears valid for a high current device, (e.g., a reactor) based on the results of a computer code developed by Petrie,⁴ the latter assumptions should hold for α 's interacting with a nearly Maxwellian background plasma. The total fraction of α 's lost through ripple effects is, then:

$$F_T(r_m, N, T) = \frac{\int_0^{2\pi} d\phi \int_{-\pi}^{\pi} d\theta \int_0^a r dr S(r) \left[\int_{\xi_L}^1 \left[\operatorname{erf}\left(\frac{\xi_L - \xi}{\sqrt{2\langle \Delta^2 \xi \rangle}}\right) + \operatorname{erf}\left(\frac{\xi}{\sqrt{2\langle \Delta^2 \xi \rangle}}\right) \right] d\xi + \xi_L \right]}{(2\pi)^2 \int_0^a S(r) r dr} \quad (3)$$

where $S(r)$ is the α source function. As rough approximations, c is taken to be independent of E , the α 's are assumed to bombard the ceiling of the reactor uniformly in the region of $R_0 < R < R_0 + a$ (which is a lower unit on the localized wall flux), and $\xi_L \ll 1$. In the latter limit $F_T \simeq 2(2\epsilon)^{1/2}$. The cost per year for 1st wall replacement,

$\frac{dC_{n+\alpha}}{dt}$ is then:

$$\frac{dC_{n+\alpha}}{dt} = \frac{dC_n}{dt} \left(1 + \frac{\Lambda_w}{\Lambda_\alpha} c F_T(r_m, N, T) \right) \quad (4)$$

where $\frac{dC_n}{dt}$ is the 1st wall replacement cost due to neutron damage, Λ_w is entire first wall area and Λ_α is that portion bombarded by α 's. Since one α is produced in a D-T reactor for each neutron the second term on the right hand side of equation (4) represents the relative α to neutron flux in the localized areas of α bombardment times the relative damage coefficient. Thus if no precautions were taken in the first wall design for this type of α bombardment equation (4) would represent the total replacement cost rate.

The total first wall replacement cost due to these two damage processes for a plant lifetime ($\Delta\tau$) is just

$$C_{n+\alpha} = \Delta\tau \frac{dC_{n+\alpha}}{dt} = \Delta\tau \frac{dC_n}{dt} \left[1 + \frac{A_w}{A_\alpha} c F_L(\bar{r}_k, r_m, N) \right] \quad (5)$$

In this approximation $F_L \propto \epsilon_a^{1/2}$ and hence is a decreasing function of r_m (see Eqn. (1)). Thus if the second term in equation (5) is significant due to a high value of c (i.e., a high first wall damage coefficient per incident α) the first wall replacement cost can be reduced by increasing r_m . The cost of the magnetic system based on current prices can be written as:⁵

$$C_m (10^6 \$) = 3.15 \cdot 10^{-3} \left[B_0^2 (kG) (r_m + r_c) R_0^2 \left(1 - \sqrt{1 - \left(\frac{r_m}{r_m + r_c} \right)^2} \right) \right]^{4/5} \quad (6)$$

where the magnetic field at the plasma minor axis, B_0 , is being held fixed. Note as expected C_m is an increasing function of r_m : increasing the magnet bore costs more. Assuming a 30 year plant life, $\epsilon_L \ll 1$, $KT \ll \bar{E} \ll E_0$, and UWMAK I parameters, an optimal r_m is found and the results are shown in Table I. Replacement costs are so high due to neutrons, \$45M/2 years for UWMAK I, that if α 's cause even a fraction of the neutron damage (i.e., $c \geq 0.1$), increasing the radius of the field coils reduces the cost of electricity. The effect of peaked source functions, $S(r)$, is relatively minor. Due to the assumptions these results should be regarded with some caution, and only as examples of a technique. However this analysis demonstrates that toroidal field ripple causes the loss of a significant fraction of the energetic α 's which bombard the first wall in very localized areas, and this localization amplifies their effective damage. Hence a thorough knowledge of the first wall damage process by α 's, neutrons and plasma ions is essential to properly optimize the magnet design of a Tokamak reactor.

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Nucl. Eng. Lab, Urbana, IL 61801
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Table I N = 12 Coils

c	Optimum r_m (meters)	$S(r) = 1 - G(\frac{r}{a})^K$		C_m (10^6 \$)
		K	G	
0.01	7.3	0	0	\$127
0.1	9.2	0	0	\$167
1.0	13.9	0	0	\$273
1.0	12.8	2	1	\$244
1.0	12.55	1	1	\$238
1.0	12.35	1/2	1	\$233
0.1	8.66	1/2	1	\$155

3. Induced Plasma Rotations

As superthermal alpha particles escape from the fusing plasma, an electric field is set up. In a tokamak, this field crossed with the poloidal magnetic field will result in a toroidal plasma rotation. Present studies of this effect, reported in T. Petrie's thesis (COO-2218-83), suggest that the rotation velocities in near-term devices are sufficient to be of interest for diagnostic measurements but not large enough to cause disruptive instabilities. For convenience, a report of some of this work taken from COO-2218-504 *Trans. Am. Nucl. Soc.*, 26, 85 (1977) is reproduced below.

8. Plasma Rotations Induced by 3.5-MeV Alpha-Particle Losses; T. W. Petrie, G. H. Miley (U of Ill)

As experimental fusion devices begin to achieve higher temperatures and densities, possible effects of fusion product production on the plasma become a crucial question. We have investigated one potential problem; namely, the radial electric field buildup and associated plasma rotation resulting from charge-imbalances created as fusion products escape the plasma. While prior studies of plasma rotation have been reported, most have not been concerned with alpha particle effects, and this represents the first to include the radial electric field in a self-consistent manner.

We consider two mechanisms for fast, 3.52-MeV alpha losses. First, energetic alphas moving in a tokamak with an axisymmetric toroidal field undergo sizable excursions from their initial flux surfaces if the safety factor q is not too low. Consequently, a portion of the alphas have orbits lying outside the plasma and they are lost. Second, alphas trapped in localized magnetic ripple wells can also drift rapidly to the plasma surface. In both cases, the alphas leave so quickly (1 to 10 μ s) that the electrons are unable to traverse the magnetic field fast enough to quench the resulting radial electrostatic field. The numerical techniques involved in the calculation of alpha transport during slowing and their loss rates are described in Ref. 2.

These fields would continuously build up if it were not for various damping mechanisms. In our treatment, we consider three damping processes: (a) ion-neutral collisions, (b) charge-exchange, and (c) angular momentum diffusion of the plasma. In the majority of cases studied,

the latter is the dominant mechanism near the plasma center, where relatively few neutrals are present; whereas, charge-exchange becomes a dominant process in outer regions of the plasma.

The steady-state radial electric field, E_r , can be written:

$$E_r = E_{r_0} - \frac{J_{\alpha}(r)}{\sigma_{\perp}}$$

where E_{r_0} is the normal ambipolar field (i.e., without fusion present), $J_{\alpha}(r)$ is the 3.52-MeV radial current density (as a function of r), and $\sigma_{\perp}$ is the perpendicular conductivity of the plasma. The latter quantity is calculated from a first-order correct fluid model,³ while $J_{\alpha}(r)$ is obtained from the transport calculation referenced earlier.

In discussing results, we consider two classes of tokamaks: (a) a high-current power reactor design (UWMAK-like), and (b) a small low-current torus (TFTR dimensions). In the former, for reasonable plasma parameter values, magnetic ripple is responsible for most 3.5-MeV losses; while in the latter, the "symmetric" trapping mode dominates.

It is found that large electrostatically induced fields are possible in the case (a) tokamak, where ripple losses can build up the radial electric field to many times the normal ambipolar field. This can result in sizable toroidal rotations as illustrated in Fig. 1. The longer and

Fig. 1. Toroidal velocity is plotted against radial position for a UWMAK-like reactor. The fusionless case is represented by the shorter dashed line, while the longer dashed line includes fusion effects.

Fig. 2. Toroidal velocity is plotted against radial position for a TFTR-like device. The dotted line represents the fusionless case. The solid line includes fusion effects.

shorter dashed lines represent toroidal rotations with and without fusion present, respectively. Due to parallel viscosity effects, it is found that poloidal rotation is essentially negligible. However, for this case, maximum toroidal speeds can approach the thermal speed. While this is not thought to be serious relative to more severe instabilities such as Kelvin-Helmholtz modes, such rotation could cause mild disruptions and represent an important feature for diagnostic purposes.⁴

In TFTR-like operating conditions, both toroidal and poloidal rotations are relatively small, largely due to increased damping encountered at the lower plasma temperatures involved. In Fig. 2, the solid line and the dashed line again represent a fusion and nonfusion situation, respectively, for the TFTR.

Thus, although the electrostatic field and plasma rotation effects are less significant in small, low-current devices, these effects can become considerably more important in larger, reactor-like tokamaks.

1. D. L. JASSBY and H. P. FURTH, PPPL report TM-271 (Jan. 1974).
2. T. W. PETRIE and G. H. MILEY, "New Techniques for Studying Some Effects of Suprathermal Alpha Particles," *ANS Mathematics and Computation Division Topical Meeting*, Tucson, Arizona (Mar. 1977).
3. A. H. BOOZER, *Phys. Fluids*, **19**, 149 (1976).
4. R. V. NEIDIGH and D. J. SIGMAR, *APS Bull.*, **21**, 1044 (1976).

4. Alpha-induced Instabilities

Work in this area is described in detail in COO-2218-85, submitted to *Nuclear Fusion*. For convenience a brief abstract from the Nov. 1976 APS Plasma Physics Div. Meeting (COO-2218-515) is reproduced below.

Some Instabilities Driven by Fusion Products,*

M. Y. WANG and G. H. MILEY, Univ. of Ill., Urbana--

Various plasma waves which are possibly excited by MeV alphas have been investigated. For a delta birth distribution it is found that: a) The right-circularly polarized Alfvén wave can be excited. Its growth rate is linearly proportional to the α -particle density. b) The drift Alfvén wave is stable against α -particles. c) For a uniform temperature, the plasma wave spectrum changes from three branches with $n_\alpha=0$ to four branches for $n_\alpha \neq 0$ case. d) α -particles can destabilize the ion drift acoustic wave even with uniform temperature. However, the ion acoustic wave appears to be stable against fusion products in a fusion grade plasma. e) If their effect on the background plasma spectrum is neglected, α -particles can excite the electromagnetic cyclotron wave in a range of harmonics (band structure). The growth rate is proportional to the square root of α -particle density. f) If the effect of α -particle on the plasma spectrum is included, we find that electromagnetic cyclotron wave is stable. The latter two points are consistent with, but extend previous studies by Kaladze et al.¹

*Work supported under U.S. ERDA Contract AT(11-1)2218.

¹T. D. Kaladze, D. G. Lominadze, and K. N. Stepanov, Sov. Phys. Tech. Phys., 19 175 (1974).

5. Alpha Impurity Build-up

As alpha particles thermalize in a tokamak, they will diffuse inward and build up to a high density at the centerline of a tokamak. This is a serious problem since rapid build-up of alpha "ash" can cause premature quenching of diffusion burn, resulting in short-pulse operation and uneconomically low Q-value. Since alpha particles are thermalized within the plasma, rather than entering from the wall, the

use of a divertor is relatively ineffective in controlling this build-up.

The present work is designed to better understand alpha particle build-up by using thermalization profiles calculated by the slowing-down technique described in Section III-1 as a source to the thermal-alpha diffusion equation. While previous studies of alpha particle diffusion have been reported, they have been limited to quite idealized thermalization sources. The most common assumption is one of "in-situ" slowing down (see Sec. III-1). The large alpha orbits, in fact, result in a broadened thermalization distribution, and this can create significant differences in predicted alpha diffusion currents. Preliminary results and studies were reported at the APS Topical Meeting on Atomic Processes in Plasmas at Knoxville, TN, February 1977. This work is contained in COO-2218-517 and the conference abstract is reproduced below.

Transport of Alpha Particles as Impurities in D-T Plasmas.* W. DOWNUM, T. PETRIE, C. CHOI, and G. H. MILEY, Univ. of Illinois, Urbana, IL.--The thermalization of high-energy alpha particles in a D-T fusion plasma is treated using a phase-space group technique, toroidal orbit theory, combined with a drift weighting technique.¹ Due to a significant departure from flux surfaces, the slowing-down density of the alphas is found to shift outward relative to their birth distribution. This has two consequences: a radial $\vec{E}$ -field is created, and the source term for thermal alpha diffusion is shifted from the normal insitu² approximation. The resulting effect on alpha accumulation is very sensitive to detailed plasma parameters, and equilibrium profiles based on a diffusion model (Cf. Ref. 2 with $\vec{E}$ -field effects) are presented. Implications relative to burn-quenching are discussed.

*Supported by US ERDA, Contract AT(11-1)-2218.

1. G. H. Miley, et al., Bull. APS, 20, 2H11, 1259 (1975).
2. D. J. Sigmar, et al., "Alpha-Particle Diffusion in Tokamak Reactors," IAEA-CN-33/A15-3, p. 595, Tokyo (1974).

6. PLT Experiment

High energy fusion-product effects will become significant as experimental devices like PLT and TFTR begin to achieve temperatures above 1 keV. We have proposed an experiment for detection of such fusion products in PLT. The purpose of the measurement is two-fold:

- (1) to test our theory of fusion product transport in fusing plasmas,
- (2) to develop such detectors for diagnostic applications.

Two detectors will be used, placed at the top and outboard side of the torus (see Fig. 4). To protect the detectors from excessive background radiation, they are shielded and face away from the plasma. The detector is designed to accept fusion products moving along gyro-helices.

The analysis of this experiment employs the same techniques developed to study wall bombardment by fusion products (Sec. III-2). The detector problem is considerably more complicated by several factors:

- (a) finding the fraction of particles which reach the detector from each interval of plasma volume;
- (b) finding the fraction of (a) that can enter the detector, i.e., the intersection of the gyro-helix plus guiding center drift motion with the conical shield;
- (c) finding the probability associated with (b).

Preliminary results for a 5 keV D-D plasma in PLT show an increase from $\leq 10^6$ to $\sim 10^9$ particles/sec at the side detector, as the plasma current rises from .2 to .6 MA; there is a much smaller variation ($\leq 50\%$) at the top detector for this same current change. There is a $\leq 50\%$ variation in both detectors as the toroidal field is changed from 20-40 kG. Since the values vary strongly with temperature (10^4 increase from 1 to 5 keV), ratios of the two detector measurements are required to eliminate the effect of the temperature rise as the discharge progresses.

Figure 4
PLT EXPERIMENT (CONT'D)

IV. Mirror System Studies

Three areas have been stressed in connection with mirror devices

- continued studies of charge-exchange during neutral beam injection (first reported last contract period)
- plasma build-up in conventional mirrors, e.g. 2X-IIB experiments
- analysis of field-reversed mirrors (FRMs).

Each area is briefly discussed below.

1. Charge-exchange during neutral-beam injection.

This problem is particularly crucial in near-term mirror devices such as MFTF because the small size of these plasmas results in the escape of large fluxes of charge exchange neutrals. This can lead to impurity problems, wall erosion, and hot spots on the wall. This work was reported in some detail in C00-2218-507 at the 2nd Topical Mtg. on the Technology of Controlled Nuclear Fusion, and in C00-2218-68P at the 9th Symp. on Fusion Technology in Garching, Germany. Parts of the latter paper follow.

INJECTION CONSIDERATIONS FOR MIRROR REACTORS

by

G. H. Miley, R. L. Miller, and M. Campbell

ABSTRACT

Monte Carlo calculations of charge-exchange losses during neutral-beam injection into small mirror devices are described. Local hot spots on the first wall are identified that have serious design consequences. Also, the twin-beam mirror (TBM) concept is described where a high-energy beam (> 200 keV) is injected into a beam-driven, mirror-confined, target plasma (< 60 keV). For a FERF device, this could relax injection requirements and provide plasma stabilization.

1.0 CHARGE-EXCHANGE EFFECTS

A fraction (f_p) of the neutral-beam will penetrate the plasma and impinge on the opposite wall, a fraction (f_t) will be trapped in the plasma, while a fraction (f_w) will be stopped in the plasma but escape via charge-exchange collisions. Both the Mirror Fusion Energy Research Facility (FERF) [1,2] and the proposed Mirror Experiment (MX) [3] will have low energies ($\bar{E}_1 < 100$ keV) and small size ($\bar{n}D \sim 10^{15}$), resulting in larger f_w than expected in later reactors. While f_w is only $\sim 10\%$, this can be serious with 10's of MW injected, especially since the loss is distributed such that a beam dump cannot be used. The resulting first-wall bombardment represents a) a major heat load, b) a sputtering problem, and c) a source of cold neutral reflux.

To handle the complex geometry involved with Yin-Yang magnets and off-center injection, we have developed a Monte Carlo (MC) computer simulation technique capable of a full 3-D representation. [4]

1.1 Test Particle Tracking in the MC Code

Neutral particles are tracked in the plasma until they are either trapped by ionization or escape. Sampling techniques allow a nonuniform plasma density and energy and a multi-dimensional rejection technique [4] is used to select a suitable charge-transfer neutral from the target ion population after each collision. A key aspect is prior tabulation of $\langle \sigma v \rangle$'s. [5]

1.2 Characterization of the Neutral Beam

The beam originates at a point $P(x_o, y_o, z_o)$ measured from the plasma centerline and is described as a right circular cone with axis orientation $I(\phi, \theta)$ relative to the central magnetic field. This represents focusing of the beam through a small aperture as is planned for FERF and MX. One-beam is used, but superposition may be employed to simulate others. The primary beam component, E_o , plus parasitic components at $E_o/2$ and $E_o/3$ are included. [1,2]

1.3 MX and FERF Calculations

Parameters for MX and FERF are given in Table I and global results are presented in Table II. In addition to the beam neutrals trapped directly by ionization collisions (55% for FERF and 46% for MX), about a third of the trapped ions originate from reionization charge-transfer neutrals. These ions have an average energy less than the plasma value (~ 51 vs. 70 keV in the FERF and ~ 39 vs. 50 keV in the MX), causing radial transport of both

Table I. Mirror Parameters Used in Calculations

	FERF	MX
Plasma half-length (m); radius (m)	2.10; 0.25	1.70; 0.6
Average ion density, $\bar{n}$ (ions/m ³); energy (keV)	9.1×10^{19} ; 70	2.4×10^{19} ; 50
Beam coordinates, $P(x_o, y_o, z_o), I(\phi, \theta)$	(-0.45, 0, -0.30) (0.98, 0)	(-0.30, -3.0, 0) (1.57, 0.79)
Primary beam energy (keV)	65.00	75.00

Table II. Global Results

PARAMETER	FERF	MX
$f_p; f_w; f_t$	0.004; 0.113; 0.883	0.053; 0.180; 0.768
$\langle E \rangle$ of f_w (keV)	59.2	43.9
P_T/P_{INJ}	0.155	0.237

particles and energy.

1.4 First Wall Bombardment

If $\tilde{E}_p$ is the characteristic target plasma energy ($E_o \approx \tilde{E}_p$), P_T is the total beam power escaping the plasma, and P_{INJ} is the injected power of that component, we find:

$$P_T/P_{INJ} = f_p + f_w \langle E \rangle / E_{INJ}. \quad (1)$$

Here $\langle E \rangle$ is the average energy of neutrals escaping to the wall and E_{INJ} is the injection energy. Using Eq. (1), the power delivered to the first wall surface by charge-transfer neutrals is ~1.47 MW for FERG and 2.21 MW for MX, corresponding to average wall loadings of 0.07 MW/m² for FERG and 0.05 MW/m² for MX on a hypothetical cylindrical surface of radius about three times the plasma radius. The bombardment distributions are indicated in Figs. 1 (A-B). In both cases, the bombardment is localized near the plasma midplane ($z=0, \theta=1.57$ rad). Peaks at A1 and B1 correspond to the penetration of the primary beam while transport through the underdense fan region gives the peaks at A2 and B2. (The trough corresponds to the plasma surface facing the injector.)

Figure 1. Bombardment Distribution for Cylindrical Surface Surrounding FERG (Fig. A) and MX (Fig. B) Plasmas.

The peak loadings, cf. Table III, represent a lower bound since a shaped first wall will be closer to the plasma in the midplane area. Also, the beam-illuminated areas (near A1 and B1) must handle a beam dump during startup or accident conditions. Further, injector ratings may be increased to allow non-classical plasma losses. [1,2]

Table III. First Wall Bombardment Peaking Factors

Peak/Average Loading	FERF	MX
A1 or B1	~4 (0.3 MW/m ²)	~14 (1.2 MW/m ²)
A2 or B2	~19 (1.3 MW/m ²)	~8 (0.4 MW/m ²)

The average energy of the wall bombardment neutrals is near 60 and 44 keV for the FERG and MX, respectively. This is lower than the plasma energy and both the wall erosion estimates and neutral-particle diagnostics must properly account for this difference.

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- [4] R. L. Miller and G. H. Miley, "Charge-Exchange in Beam-Driven Mirror Devices," 6th Symp. on Eng. Problems in Fusion Research, San Diego, CA (1975).
- [5] R. L. Miller and G. H. Miley, "Ionization and Charge Exchange Rate Coefficients for CTR Calculations," ERDA Report COO-2218-26, Univ. of Illinois, Urbana, IL (1975).
- [6] G. H. Miley and R. L. Miller, "Injection Requirements for a TBM," 6th Symp. on Eng. Problems in Fusion Research, San Diego, CA (1975).
- [7] R. F. Post, *et al.*, Phys. Rev. Letters, **31**, 280 (1973).
- [8] T. K. Fowler, "Two Component FERG," UCID-16466, Lawrence Livermore Laboratory, Livermore, CA (1974).

The key to this analysis is the use of Monte Carlo methods. This is particularly important for mirrors where the complicated Yin-Yang geometry almost precludes other approaches. For convenience, a brief description of the methods used is reproduced here from COO-2218-71.

MONTE CARLO TECHNIQUES FOR NEUTRAL BEAM INJECTION STUDIES--Ronald L. Miller and George H. Miley.

Central to the development of magnetic-mirror-confined fusion reactors is a clearer understanding of the influence of the neutral-beam injection process on such crucial aspects of the overall engineering design of such machines as the total system energy balance and the thermal/mechanical design of the first wall. While simple analytic and numeric models have proven useful in identifying the salient problem areas associated with the design of the integrated injector/plasma/wall system, a more thorough approach seems in order. To that end, a steady-state, 3-D Monte Carlo (MC) computer code has been developed and applied to the simulation of energetic neutral-beam injection into near-term mirror devices (e.g. the Mirror Experiment (MX) and the Fusion Engineering Research Facility (FERF)). Important plasma engineering information, heretofore unavailable, regarding the trapping of the neutral beam in the target plasma and the angular and energy distributions of the charge-transfer-produced neutral particle bombardment of the first wall has been obtained.¹

Use of the MC method, originally developed and refined for neutron and gamma-ray studies in fission systems, results from recognition of the essential correspondence between the transport of neutral particles in a plasma medium and these conventional transport problems.² The MC approach is particularly appropriate insofar as it can treat both the complex 3-D plasma geometries of Yin-Yang mirror systems and the anisotropic plasma phase space distribution.

Figure 1 gives a schematic representation of the nonanalog MC simulation. After specification of the relevant geometry and target plasma operating conditions, a large number ($\sim 3 \times 10^5$) of hypothetical neutral particles are tracked to give an approximate, statistical picture of the consequences of the competing charge transfer and ionization collisions. The neutral test particles (grouped in cycles for bookkeeping purposes) are advanced through the plasma along a sequence of connected line segments between interaction points. The distance between interactions is sampled using a general scheme³ which allows treatment of the spatially non-uniform plasma density without resorting to inconvenient numerical integration over the cross sections and path length. This sampling scheme involves: (a) sampling the distance to a tentative interaction using a constant total macroscopic cross section, $\Sigma_T(S)$, where S is the particle position prior to this sampling of a tentative interaction point, (b) advancing the test particle to the tentative interaction point, (c) possibly altering the particle weight estimator, and (d) either accepting the tentative point as a "real" interaction point or rejecting it and returning to (a). At the interaction point, the ionizational trapping and consequent depletion of the neutral beam is calculated. Then, an ion is selected from the background population to represent the neutral particle produced in charge transfer collisions. The selection of this next-generation neutral test particle is accomplished using a multidimensional rejection technique.⁴ Eventually (< 10 generations)

the neutral particle weight estimator falls below a critical value such that its influence on the results is negligible, at which point it is terminated using a standard "Russian Roulette" procedure or the plasma boundary is crossed and the neutral particle is advanced to the first wall surface. At the first wall, the angular and energy distributions of the incident neutrals can be tabulated and used to estimate the nonuniform heating and sputtering-induced wall erosion.

A key aspect of the overall simulation is the prior calculation and tabulation of the charge transfer and ionization interaction rate coefficients, $\langle\sigma v\rangle$, as functions of neutral test particle speed and orientation w.r.t. the anisotropic target plasma phase space distribution. The details of this generalized calculation are described elsewhere.⁵ Using these rate coefficients, the macroscopic cross section used in the MC path length estimating procedure mentioned above becomes $\Sigma_T \equiv n \langle\sigma v\rangle_T / v_0$, where n is the local plasma density and v_0 is the test particle speed.

In summary, the MC simulation approach discussed here provides a powerful and versatile technique for resolving some of the important engineering questions for mirror fusion devices that involve the transport of energetic neutral particles. As some of the restrictive assumptions of this approach are relaxed, one can expect future applications to provide detailed information that can be integrated into the continuing designs of such machines.

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2. E. Greenspan, "The Calculation of the Transport of Neutral Atoms in Highly Ionized Plasmas Using Neutron Transport Methods," MATT-1001, Princeton Plasma Physics Laboratory (1973).
3. L. L. Carter, E. D. Cashwell, and W. M. Taylor, "Monte Carlo Sampling with Continuously Varying Cross Sections Along Flight Paths," Nuclear Science and Engineering, 48, 403-411 (1972).
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Fig. 1. MONTE CARLO SIMULATION SCHEME

2. Plasma Build-up

A mirror plasma is very susceptible to charge-exchange losses on the outer surfaces during build-up. This occurs because cross-field diffusion is too slow to replace plasma lost from an outer layer or "ring." The main plasma source in this layer is the trapped neutral beam, and this must be balanced against charge-exchange losses due to cold gas that inevitably finds a way to reach the plasma surface. Indeed, such problems have been observed and studied during plasma build-up in the 2X-IIB device at LLL. The present work is intended to extend the finite gyro-radius build-up code used at LLL to analyze such experiments by adding more detailed energy and magnetic field dependences. This is briefly described in COO-2218-73, reproduced below and prepared for the 4th IEEE International Conference on Plasma Sciences, Troy, NY, 1977.

An Improved Treatment of Plasma Buildup in a Mirror Fusion Device.*
 MARK CAMPBELL, C. CHOI and G. H. MILEY, Fusion Studies Lab., U. of Ill., Urbana, Ill.--An improved plasma buildup model in a mirror fusion device, allowing effects due to finite ion gyroradius, magnetic field gradients, radiation loss, and high Z-impurities trapping, is considered. The plasma is modeled as being composed of concentric spatial shells with the ions in each shell resolved into energy groups. The spatial (and energy) dependences are coupled due to the fact that the density at any point in the plasma represents a time-averaged contribution from all particles whose gyro-orbits pass through that point (the orbits being dependent on particle energies). In a small device ($R_p < 25 \bar{r}_q$) many ions will contribute to the density over a fairly large region of the plasma, making a finite gyro-radius (F.G.R.) treatment mandatory to obtain an accurate radial density profile.(1)

For rapid survey calculations, it is expeditious to use a simplified version of this model which employs a single-shell energy dependent "module." This code, based on a 1-D Fokker-Planck treatment, has been employed in a comparison study of conventional vs. "twin beam" mirror devices.(2) The conventional mirror results are generally in good agreement with those of Futch, et al.(3) (other "twin-beam" studies are not available).

To fully evaluate the "twin beam" concept a study of the effect of beam injection angle on plasma buildup is currently underway using an extended 2-D Fokker-Planck treatment.

1. B. W. Stallard, "Radial Plasma Buildup Code for Neutral Beam Injection into a Mirror Machine," UCRL-51784, TID-4500 (March 1975).
2. G. H. Miley and R. Miller, "Injection Power Requirements for a Twin-Beam Mirror Fusion Device," ANS Conf. Proc., San Francisco (1975).
3. A. M. Futch, et al., "Multispecies Fokker-Planck Calculations for D-T and D-³He Mirror Reactors," Plasma Physics, 14, pp. 211-244, (1972).

Complementary to this work was a study done to determine the effect of high energy beam injection angle in a "twin-beam mirror" (T.B.M.) system that has been studied as an alternate concept for a Fusion Engineering Research Facility (FERF) (see *COO-2218-56P*). The results of this study weighed heavily in a decision not to incorporate a 2-D Fokker-Planck treatment in the finite gyro-radius build-up code. This is described in *COO-2218-87* reproduced below.

EFFECT OF HOT BEAM INJECTION ANGLE

ON TWIN BEAM MIRRORS

by

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The purpose of this work is to study the effect on fusion power density of injecting the high energy beam component in a "twin beam mirror" (T.B.M.) device at an acute angle, rather than perpendicular, to the magnetic field. Increasing the power density for T.B.M. is desirable for its use in a Fusion Engineering Research Facility (F.E.R.F.).

Previous work has shown that injecting a small current of high-energy neutrals into a conventional beam-driven mirror fusion system can lead to a considerable reduction in the injection requirements needed to achieve a given fusion power output,¹ but at the cost of a lower maximum power density compared to an equivalent conventional mirror. This occurs

because trapped high-energy beam particles contribute heavily to the total plasma pressure, greatly reducing the maximum plasma density attainable without exceeding β limitations. It has been suggested² that injecting the high energy beam at an (acute) angle rather than perpendicular to the magnetic field may reduce the perpendicular pressure ($P_{\perp}$) of the hot ions without unacceptably decreasing their confinement time. This would allow one to inject more high and/or low energy beam to fill the perpendicular pressure back out to the β limit and compensate for any enhanced hot-ion loss rate, yielding the desired increase in power density with, hopefully, only a modest decrease in Q (fusion power/injected power).

Theoretical calculations carried out for a conventional mirror^{3,4} indicate that for a very acute injection angle approaching the loss cone angle there is an increase in the β limit and fusion power density but not decreases rapidly, resulting in an overall optimum for injection near 70° , typically. However, there are significant differences between this case and T.B.M. For example, the low velocity-space scattering rate for hot ions (until slowed to near-thermal velocities) permits having a significantly different velocity-space distribution for the hot ions (supported by the high energy beam) compared to that of the cooler background ions (supported by the low energy beam). This can greatly affect the velocity-space averaged cross sections ($\langle\sigma v\rangle$'s) for fusion, Coulomb scattering, and energy transfer between hot and cool ions.

The difficulty of treating the diverse factors arising from non-perpendicular hot beam injection was overcome by using a 2-D nonseparated multispecies Fokker-Planck code (with a self-consistent plasma potential calculation) obtained from L.L.L.⁵ This code was modified to calculate the perpendicular pressure contribution of each species by averaging $v^2 \sin^2 \theta$ over the velocity distribution, where θ is the (acute) angle of the velocity vector ($\vec{v}$) to the $\vec{B}$ field. To improve the resolution of high energy beam effects, trapped hot beam ions were tracked as a separate species from those injected via the low energy beam (both species having identical charge and mass). Electrons were also treated as a species.

Table I gives the results for a typical T.B.M. plasma as a function of injection angle, for fixed trapped currents, normalized to the perpendicular case. The rapid monotonic decrease in hot ion density or, equivalently, confinement time is not accompanied by any significant decrease in the

perpendicular pressure contribution because energy transfer between the hot and background ions decouples, causing $\langle v^2 \sin^2 \theta \rangle$ to remain nearly constant for injection at $>55^\circ$. Below 50° , the rapid loss of hot-beam ions raises high-energy injection requirements $>75\%$ which drops Q and destroys much of T.B.M.'s advantage of reduced injection. More detailed calculations show that in the neighborhood of $50-55^\circ$ injection one can obtain about a 1% increase in power density for every 1-2% decrease in Q up to a 5-8% net increase (this includes an increase of approximately 10-20% in $\langle \sigma v \rangle$ for fusion between hot and background ions). This is done optimally by injecting enough high energy beam to maintain the same hot density obtained for perpendicular injection and filling out to the β limit with background plasma.

In summary, it is possible to obtain an increase in the T.B.M. fusion power density of as much as 8%, at the cost of a similar percentage drop in overall system Q , by injecting the high energy beam at a $\sim 50^\circ$ angle to the magnetic field. For injection at $<50^\circ$ the drop in Q is large enough that the T.B.M. loses most of its injection advantages over conventional mirrors.

INJECTION ANGLE	BACKGROUND ION ENERGY $W_C/W_{C\perp}$	HOT ION ENERGY $W_H/W_{H\perp}$	HOT IONS $\frac{\langle \sin^2 \theta \rangle}{\langle \sin^2 \theta \rangle_\perp}$	HOT DENSITY $n_H/n_{H\perp}$	$\frac{P_\perp}{W_{H\perp} \langle \sin^2 \theta \rangle_\perp}$
90°	1	1	1	1	1
66.5°	0.996	1.06	0.94	0.93	1
60°	0.990	1.09	0.92	0.87	~ 1
55°	0.987	1.12	0.89	0.80	0.997
52.5°	0.983	1.13	0.84	0.76	0.949
50°	0.98	1.13	0.82	0.70	0.927
45°	0.96	1.14	0.79	0.58	0.900

Table I: Plasma parameters for typical TBM vs. injection angle, normalized to the perpendicular injection case.

An average mass for D-T of 2.5 amu was used in the calculation. The hot beam energy of 300 keV was chosen on the basis of sufficiently good trapping in a 25 cm. radius plasma.

W_e , the electron energy, was constant within $\pm 1\%$ for all runs.

n_c , the background density, fell with $n \propto W_c^{3/2}$ to -2% at 45° injection.

All values are for 90/300 keV injection at a trapped current ratio of 10:1.

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3. Field-Reversed Mirror Studies

The field-reversed mirror (FRM) concept has two very important advantages:

- a higher Q than conventional mirrors, i.e. it and the tandem-mirror are currently viewed as the leading contenders for Q -enhancement of mirror systems
- a small size which could result in relatively low-capital-cost power plants that utilities could afford for special purpose applications to supplement larger central site units.

As illustrated in Fig. 5, the Fusion Studies Laboratory effort is based on the development on a comprehensive treatment of the plasma systems aspects of the FRM.

Figure 5. Plasma System Components for FRM Studies.

A basic contribution to this area, first noted in last year's progress report, is the recognition that an analogy with Hill's vortex allows a particularly simple representation of the reversed field configuration. This concept has been used to study and classify the ion orbits in the FRM. A detailed discussion of these results is presented in COO-2218-508, submitted to *Nuclear Fusion*. A summary of this work from COO-2218-512 and presented at the recent *Sherwood Theory Meeting* at San Diego is reproduced below.

With the recent achievement of high beta in 2X-II⁽¹⁾, the concept of a field reversed mirror (FRM) created by internal plasma currents has gained in interest. In contrast to the Astron concept, the FRM utilizes lower energy neutral beam injection, thereby allowing a smaller device⁽²⁾⁽³⁾. In the present work we study particle orbits for the FRM based on an analogy with the spherical vortex configuration originally developed by M. J. Hill⁽⁴⁾. With this method analytic solutions are obtained. For motion in the midplane, the orbits can be written in terms of 1st and 3rd kind elliptical integrals. Requirements for absolute confinement are obtained, and four distinct classes of orbits are identified that are bound by limits on the canonical angular momentum P_θ . The improvement in confinement over a simple mirror as well as natural divertor properties of the FRM are shown by these results. Implications of the orbit classification to diffusion flow are under study. It is thought that an "effective" diffusion coefficient can be derived using these results, and this can in turn be used in reactor design studies.

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Results from these orbit studies have been combined with global plasma and energy balance equations in an overall FRM plasma code as illustrated in Fig. 6. This code is distinguished from other existing FRM treatments by use of an energy group approach, self-consistent magnetic fields, and a self-consistent treatment of diamagnetic flows. This area is aimed at the development of techniques to analyze the plasma systems aspects of the FRM.

Figure 6. Global Code Model of the FRM

The first application of the code was to examine the possibility of a small D-³He FRM device. Companion investigations of D-T devices are in progress. D-³He was selected in these initial studies, however, since this would supplement the D-T studies in progress at LLL and since advanced-fuel fusion is of interest relative to a separate EPRI contract at Illinois. Preliminary results from this analysis are indicated below based on COO-2218-503, published in *Trans. Am. Nucl. Soc.*, 26, 53 (1977).

1. Approaches to Small-Size Field-Reversed Mirror Reactors, G. H. Miley, D. Driemeyer (U of Ill)

While most conventional approaches to magnetic fusion lead to large-size power plants, the field-reversed mirror (FRM) potentially offers an attractive small size unit. We have explored the possibility of capitalizing on this feature through development of a D-³He-fueled FRM that would serve as a satellite to larger D-T or cat-D reactors.¹ To facilitate our study, we extended the plasma model of Condit et al.² to include an explicit treatment of the "circulating" injected ions, a diamagnetic current estimate, and a pressure instability limited diffusion rate.

Interest in FRMs has intensified with promising high- β results from the 2X-II experiment at Livermore. The concept is not new but the approach is. In the FRM, internal plasma currents, rather than single gyroradius high-energy electron or ion beams, maintain the magnetic field reversal. This makes initiation of reversal by neutral-beam injection at sub-MeV energies conceivable. The resulting closed-field line region provides improved confinement, while the surrounding mirror field is compatible with electrostatic direct energy conversion. It is this compatibility with direct conversion processes that makes the FRM so attractive for burning advanced fuels. Thus, as shown later, good overall plant efficiencies can be achieved with a modest energy multiplication factor ($Q_p \sim 1$).

To provide a consistent check on the field-reversal requirement, it is necessary to calculate the net plasma current. The contribution from the injected ions is found by evaluating the contribution of contained orbits associated with superthermal ions prior to randomization by collisions. In addition to creating a current, these ions contribute to fusion by beam target reactions. A dia-

as the ratio of the diffusion coefficient employed to that for classical diffusion. A rapid turbulent diffusion is assumed to occur when the local β exceeds pressure balance requirements.

Table I summarizes reactor parameters for three separate designs. Cases A and B illustrate the effect of injection energy, while cases B and C represent different reactor sizes. Case A is the most efficient with ~46% overall efficiency. This, however, is achieved using a relatively high injection energy of 600 keV. Case B (300-keV injection) gives an attractive reactor, but the efficiency falls to ~36%. The preceding designs have quite modest sizes, ~120 litre. Case C shows that even smaller units, ~50 litre, are possible, but at the sacrifice of efficiency.

Figure 1 shows the plasma output power split vs injection energy for Case C. A striking feature is the large fraction of output power carried by charged particles. The sum of leakage and charged fusion power output is always $\leq 70\%$, making it possible to obtain a reasonable overall efficiency despite the relatively low Q_p . The increased charged-particle power at higher injection energies generally accounts for the increased overall plant efficiency for Case A of Table I.

With neutron powers generally $\geq 7\%$, radiation emission becomes the dominant energy flux on the first wall. This, plus freedom from tritium breeding requirements, makes possible the use of a high-temperature helium-cooled graphite blanket. This, in turn, permits good thermal efficiency with minimum prospects for radiation damage.

While field reversal has not yet been demonstrated experimentally, both 2X-II experiments and plasma simulation studies are very encouraging. The present conceptual design does not represent a large extrapolation in

TABLE I
Reactor Parameters for Three FRM Designs

	A	B	C
Vacuum Field (kG)	60	60	60
Injection Current (amp)	4.5	14.0	7.5
Injection Energy (keV)	600	300	300
Ion Temperature (keV)	102	68	77
Electron Temperature (keV)	65	48	48
Background Density (cm ⁻³)	4.6×10^{14}	7.7×10^{14}	6.6×10^{14}
Circulating Density (cm ⁻³)	5.7×10^{13}	6.4×10^{13}	8.8×10^{13}
γ_B	1.7	2.2	2.1
γ_C	21	35	31
Confinement Time (s)	3.2	1.0	.72
Plasma Volume (litre)	118	118	50
Neutron Wall Flux (cm ⁻² s ⁻¹)	2.4×10^{13}	4.4×10^{13}	2.8×10^{14}
Fusion Power (MW)	1.7	2.9	1.1
Energy Multiplication (Q_p)	1.4	1.0	.72
Net Power Output (MW)	.79	1.05	.22
Overall Efficiency ^a (%)	46	36	20

^aAssumes injection, direct conversion, and thermal effs of 80, 85, and 50%, respectively.

magnetic current created by cross-field diffusion also contributes to field reversal, and the total current is the sum of this component plus the injected component. The ratio of the total current to the injected current is defined as γ_B , which typically ranges from 1 to 3. Because there remains an uncertainty about the type of diffusion to be expected in the FRM, a factor γ_C is also included, defined

Fig. 1. Energy split for the D-³He FRM.

size, fields, etc. compared to next-generation mirror experiments. Consequently, if reversal is indeed demonstrated, concepts such as those proposed here must be viewed as realistic near-term objectives.

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V. Other Studies

1. Field-Reversed Pinch (FRP) Burn Stability

The Field-Reversed Pinch (FRP) represents a possible alternate to tokamaks which potentially offers the advantages of higher beta and large aspect ratio. One problem, however, is that the short burn time of the FRP results in a relatively high pulse rate. This has the disadvantage of requiring frequent transfer and storage of comparatively large amounts of energy between pulses. The present work is aimed at the study of stability limitations and possible techniques for control and lengthening the burn. First, results are presented in the M. S. Thesis of Helen Stimpson COO-2218-78 , and a summary, taken from COO-2218-90 (submitted, *Trans. Am. Nuclear Soc.*) is reproduced here.

Burn Stability in a Reversed Field Pinch

by

Helen R. Stimpson and George H. Miley

A global computer model which simulates the burn of a plasma in a reversed field pinch (RFP) device has been developed and applied to various prospective methods of prolonging plasma stability. The applied voltage and magnetic field can be input directly because the code uses a unique plasma model incorporating a helical current form to calculate θ (analogous to q for tokamaks--see Fig. 1). Results show that the plasma radius and applied magnetic field have a strong influence on θ at the time of peak voltage; consequently careful selection of these parameters is crucial if an extended burn period and the associated enhanced energy multiplication are to be achieved.

Since large aspect ratios are possible with the RFP, this configuration offers many advantages^{1,2} in device construction and maintenance. The plasma is thought¹ to be stable for high β . Its stability is, however, subject to the Suydam criterion³ and to the necessity of

Figure 1. Operating curves for different values of plasma radius, a . [$\beta \equiv (\text{plasma pressure})/(\text{magnetic pressure})$ and $\theta \equiv (\text{poloidal magnetic field at plasma edge})/(\text{average toroidal magnetic field})$]

avoiding magnetohydrodynamic kink instabilities⁴. These constraints restrict^{1,5} the plasma in β - θ space to fall within the broken lines of Fig. 1. For a reactor such as considered here (typical of early Culham designs), stability, rather than excessive wall loading or α particle accumulation, often presents the limitation on extended burns.

The code monitors β and θ continuously making a stability plot of the burn (e.g. Fig. 1) possible. This is accomplished through modeling⁶ the plasma current in the helical configuration thought appropriate to the reversed field pinch. The characteristic electromagnetic decay time suggested by Adlam and Taylor⁷ is used. The resistivity of this turbulent plasma is found from the formulation of Spitzer and Härm⁸ for low ($kT_e \leq 0.5$ keV) temperatures but is held constant⁹ at higher ones. Current decay has negligible effect in the short times discussed here but will become significant if longer burns are accomplished. Since the code cannot adequately model the initial cold and very turbulent regime, a nonzero initial voltage is used and initiation of field reversal is assumed.

Parametric studies have been performed using a reference reactor with major radius 15 m, plasma radius 3 m, imposed magnetic field 1 T, voltage rise time 1 s and an initial ion density of $7 \times 10^{19} \text{ m}^{-3}$ (50:50, D:T). Results of varying the plasma radius are shown in Fig. 1. As indicated on curve A, the plasma does not follow the β - θ trajectory at constant speed. The 'knee' of the operating curve (at ~ 1 s on curve A) corresponds to the peak applied voltage and the start of the burn. After this point, the current, and hence θ , vary only slowly while β increases rapidly because of fusion heating.

The position of minimum θ , the 'knee' of the operating curve, is most sensitive to the plasma radius and imposed magnetic field. (Other parameters such as maximum voltage and voltage rise time have noticeable but smaller effects on 'knee' location.) To extend the stable burn period, it is essential that the 'knee' be as close to the upper limit of θ as stability permits. (Based on experimental observations, kink instabilities are not crucial during the fast formation period prior to the 'knee'.) This can be achieved using reference reactor parameters but with a 5 m plasma radius (case A of Fig. 1). To obtain similar results with the 3 m radius of the base case, the imposed field must be decreased to ~ 0.7 T. The importance of this positioning is evident from a comparison of cases A and B of Fig. 1. Decreasing the plasma radius from 5 m to 4 m shifts the 'knee' to $\theta \sim 1.4$; this shortens the burn from 6 s to 5 s and so reduces Q from 2 to below unity.

Unfortunately, this strategy allows little control over operation after peak voltage is achieved. To modify the burn trajectory at later times (e.g. after 4.5 s for curve A) it is necessary either to increase θ or to decrease $d\beta/dt$, or both. Potential methods of reducing $d\beta/dt$ include cold fuel injection, perhaps using pellets; and plasma cooling by de-compression. Neutral-beam driven currents can increase θ , but at the expense of added energy input. Such procedures are now under evaluation.

In summary, a description of the RFP has been developed using a helical current model to monitor the trajectory of θ during the burn. Results show that proper selection of key parameters, specifically plasma minor radius and imposed magnetic field, are essential to initiate the burn in the most favorable region for extended stability.

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2. Unified Slowing-Down Theory

The Unified Slowing-Down Theory described in COO-2218-505 (reproduced below) has the advantage that, on a theoretical basis, it has a broader range of applicability than conventional Fokker-Planck treatments. Its usage in fusion studies to date has been limited, however, due to a fear that computational times would be excessive. As developed here, the computational time appears to be competitive with Fokker-Planck treatments. Admittedly, this has required the introduction of several approximations in the unified theory, but this is not thought to be serious, at least for the regime of plasmas of interest for magnetic confinement. Some problems may occur in applications to super-dense inertial cases, however, so the more complete version of the theory should be retained in such cases. The summary below is from *Trans. Am. Nucl. Soc.*, 26,81 (1977).

4. Application of a Unified Slowing-Down Theory to Fusion Plasmas, C. Choi (U of Ill), C. Bathke (Princeton PPL), G. Miley (U of Ill)

An accurate treatment of the slowing-down problem is important to fusion applications in three areas: neutral-beam heating; two-component fusion; and ignition via fusion product heating.

Both conventional collision and the wave theories¹⁻⁴ encounter difficulties through "divergences" of the Coulomb logarithm. A "unified" theory^{5,6} combines both theories in a manner such that the artificial introduction of interaction limits, i.e., the Debye screening and the close impact radii, is no longer required. In the present work we develop a numerical method to implement the unified theory. As an illustrative application, the slowing down of fusion-born alpha particles computed in this fashion is compared here to a Fokker-Planck treatment^{7,8} and to results by Sigmar and Joyce,¹ as well as Rose.⁴

The unified theory employed is exact to order g_s , the small plasma parameter,⁹ and is solved using Romberg numerical integration techniques.¹⁰ The energy loss rate dE/dt of a charged particle is found as a function of various plasma parameters, and the slowing-down time between energies E_0 and E ; $\tau_s(E; E_0)$ is then evaluated from

$$\tau_s(E; E_0) = \int_{E_0}^E \frac{dE'}{dE(E')/dt} \quad (1)$$

A unique aspect of this work is the formulation of the unified theory; i.e., the describing relations for dE/dt in a way that is readily amenable to numerical treatment.

For a test case of fusion product slowing, we assume: a 50/50 D-T plasma; $n_e = 1.0 \times 10^{14} \text{ cm}^{-3}$, and $n_d = n_t = n_e/2$, with $T_d = T_t = 100 \text{ keV}$, and $T_e = 80 \text{ keV}$, 40 keV,

and 20 keV. (The temperatures are representative of mirror-type fusion plasmas.) A comparison of slowing-down times is shown in Fig. 1. As expected, due to the more precise inclusion of collective and collision phenomena, dE/dt for the unified treatment is larger (i.e., τ_s is smaller) than for the FP (Fokker-Planck) or SJ (Sigmar Joyce) models. For DJR (Rose) τ_s value is even smaller than that of the unified treatment, but this is due to some approximations and to erroneous identification of constants. (This large discrepancy was noted but not explained in S-J's earlier studies.¹)

It is interesting to note that Burke and Post^{11,12} recently measured the energy loss rate of fast ions moving in a dense magnetized plasma. They find a higher dE/dt than is predicted by May's modified FP calculation.¹³ The present computational results of the unified theory are in better agreement with the measurement.

Similar calculations for the injection (such as in neutral beam heating) of 150-keV deuterium ions into a tritium and a pure ^3He target plasma have also been performed. Some results are illustrated by the energy multiplication (F-value) plot in Fig. 2. The more rapid thermalization predicted by the unified theory results in a marked reduction in maximum F-values in a TFTR-type beam-driven device.

As adopted, the unified formalism does not involve any more complexity in computational methods than do less sophisticated treatments, yet the unified scheme provides confidence that the results should be valid over a wide range of conditions where assumptions inherent in other theories fail. Thus, the unified theory potentially offers an important and quite usable method for fusion plasma calculations.

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Fig. 1. Comparison of slowing-down times of the unified theory (denoted as UT) with others at $T_e = 80$ keV, $T_i = 100$ keV, and $n_e = 1.0 \times 10^{14} \text{ cm}^{-3}$ for alpha particle injected into a D-T plasma. Here DJR denotes Rose, SJ Sigmar and Joyce, FP Fokker-Planck theories from Refs. 4, 1, and 7, respectively. The Butler-Buckingham (BB) treatment from Ref. 8 has been included.

Fig. 2. F-values for injection of deuterium into a pure tritium target plasma with $1.0 \times 10^{14} \text{ ions/cm}^3$. Dashed curves are obtained from Ref. 14. Both use $E_f \sim 22.4 \text{ MeV}$.

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Compliance Statement

The work reported here has been carried out in a manner which fully complies with the original U.S. E.R.D.A. contract requirements. The principal investigator has devoted a minimum of 10% of his time during the academic year and 25% during the summer to this work.

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