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ALPHA-PARTICLE LOSSES IN COMPACT TORSATRON REACTORS*

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ABSTRACT *Loss of alpha particles in compact torsatron reactors is studied. For 6, 9, and 12 field period reactors, the direct loss is a relatively weak function of radius and energy and varies from $\approx 33\%$ for $M = 6$ to $\approx 18\%$ for $M = 12$. Loss of alpha particles through scattering into the loss region is calculated using the Fokker-Plank equation for fast ions and found to contribute an additional alpha-particle energy loss of $\approx 15\%$. The consequences of these relatively large losses for torsatron reactor design are discussed.*

The relationship between the direct particle losses and the magnetic field structure is also studied. Orbit losses from a variety of stellarator configurations are calculated and a figure-of-merit that characterizes the orbit confinement of a magnetic configuration is deduced from these calculations. This figure-of-merit is used to show how the direct losses might be reduced at low aspect-ratio. Effects of finite beta on the direct particle losses are also addressed, and are shown to significantly increase the direct losses in some configurations.

The compact torsatron sequence¹ is a family of low aspect-ratio $l = 2$ torsatron configurations optimized for high-beta operation. These configurations make interesting reactor candidates because they have the capability for high-beta operation in the second stability regime, possess natural divertors, and have relatively open coil geometry for access to the plasma. Compact torsatrons are, however, optimized for MHD properties, not orbit confinement. A large fraction ($\approx \frac{1}{3}$) of particles in these devices are trapped in the relatively large helical ripple in the magnetic field strength B . Toroidal effects at low aspect ratio cause orbits of these trapped particles to deviate significantly from flux surfaces leading to increased transport and in some cases to loss of the particles from the confinement region. Radial electric fields which develop to maintain quasineutrality of the plasma can reduce the deviation of the trapped particles from the flux surface through $E \times B$ orbit rotation, but only for those particles which have kinetic energies less than their potential energies

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in the electric field. Energetic particles created by fusion reactions or through external plasma heating will not be affected by radial electric fields and many of these energetic particles may be lost from the plasma region. The confinement of energetic alpha particles in compact torsatron reactor configurations is addressed in this paper.

CALCULATION OF ALPHA-PARTICLE LOSSES

The complicated magnetic field structure at low aspect ratio and the large particle energies of interest here make a numerical treatment of the particle loss fraction necessary. Direct particle losses were calculated by computing collisionless guiding center orbits²⁻⁵ for a distribution of alpha particles launched randomly from a given flux surface. Details of the calculation can be found in reference 6. Each particle was followed until it left the plasma volume, made two poloidal revolutions, or exceeded a preset time cutoff (several hundred helical bounce periods). Magnetic coordinates² were used so that only the magnitude of the magnetic field and not its vector components was needed in the calculation. The magnetic field strength was represented by a double Fourier expansion in the poloidal (θ) and toroidal (ϕ) angles

$$B(\rho, \theta, \phi) = \sum B_{n,m}(\rho) \cos(n\phi - m\theta) \quad (1)$$

using 12 to 25 terms. Here the normalized radial coordinate (ρ) is proportional to the square root of the toroidal flux.

ALPHA-PARTICLE LOSSES FOR REFERENCE REACTORS

The fraction of alpha particles confined is shown versus the radial coordinate ρ in Fig. 1 for three minimum radius reference reactors⁷, ATR-1, ATR-2 and ATR-3. ATR-3 is the ATF⁸ configuration scaled up to reactor size (aspect ratio 7.78, 11.1 meters major radius) while ATR-1 and ATR-2 are lower-aspect-ratio configurations (aspect ratio 3.87, 8.4 meters major radius for ATR-1; aspect ratio 4.66, major radius 10.5 meters for ATR-2). The magnetic field strength at the magnetic axis is 5 T in all cases and the particle energy is 3.5 MeV. The alpha-particle gyroradius

is 2-3% of the plasma radius. The direct particle loss fraction is a relatively weak function of radius and is smaller for the higher aspect ratio ATR-3. The difference in the alpha-particle loss fraction is due to a smaller trapped particle fraction for ATR-3 and to better confinement of the trapped particles. ATR-3 confines 60% of the trapped particles that start at $\rho = 0.25$ while ATR-1 and ATR-2 lose nearly 100% of trapped particles starting from the same radius. This can be seen in Fig. 2 where the fraction of trapped particles lost is shown versus the pitch-angle parameter for ATR-3 and ATR-1. Deeply-trapped particles (those having small pitch angles) are confined in ATR-3 but not in ATR-1.

Alpha particles and energy are also lost when particles scatter into the direct loss region. Energetic alpha particles slow down and give up their energy to the background electrons without undergoing significant pitch-angle scattering until they reach energy $E_{crit} \simeq 32T_e$. Below E_{crit} pitch-angle scattering on the background ions becomes important and most alpha particles find their way into the loss region before they can slow down enough to become confined by the radial electric field, thus preventing the accumulation of helium ash. The additional energy and particle losses due to alpha particles scattering into the loss region can be estimated from known solutions to the Fokker-Plank equation for fast ions⁹⁻¹¹. The additional energy losses estimated this way are $\approx 15\%$, but $\approx 80\%$ of the alpha particles are lost before thermalizing.

The total (direct plus indirect) loss of alpha heating power is 32 % for ATR-3 and 46 % for ATR-1 for alpha source profiles of the form $(1 - \rho^2)^4$ which corresponds to parabolic density and temperature profiles. The main implications of this loss are to increase the plasma temperature at ignition and the external heating power required to reach ignition. Once ignition is reached, the alpha-particle loss region is beneficial; it aids in burn control by reducing the amount of heat available to the thermal excursion, prevents thermalized alpha particles from accumulating in the plasma, and channels the particle energy into narrow helical stripes on the outside of the torus where it can be recovered efficiently.

DEPENDENCE ON THE MAGNETIC FIELD STRUCTURE

In order to understand how the direct particle losses depend on the structure of the magnetic field and possibly how they might be reduced, the orbit confinement

characteristics of a number of idealized stellarator configurations and a number of variant compact torsatron configurations were also investigated. In this section, the plasma radius is 2 m, the magnetic field strength on axis is 5 T, and the alpha-particle energy is 3.5 MeV. The idealized stellarator configurations have B of the form

$$B(\rho, \theta, \phi) = B_0[1 - \epsilon_{ta}\rho\cos(\theta) + \epsilon_{ha}\rho^2\cos(6\phi - 2\theta)] \quad (2)$$

where ϵ_{ha} is the helical ripple at the plasma edge and ϵ_{ta} is the inverse plasma aspect ratio. The fraction of trapped alpha particles lost versus the ratio $p_2 = \epsilon_{ha} / \epsilon_{ta}$ is shown in Fig. 3 for aspect ratios 5 and 10. The fraction of trapped particles lost is approximately independent of aspect ratio for a given value of p_2 , is nearly unity when $p_2 = 1$, and decreases on either side of $p_2 = 1$.

The results shown in Fig. 3 can be understood on the basis of the B_{min} model. B_{min} surfaces are surfaces of constant

$$B_{min}(\rho, \theta) = \min_{\phi}[B(\rho, \theta, \phi)]$$

and in the absence of radial electric fields are good approximations to deeply-trapped particle orbits. Particles that are not deeply trapped also tend to drift along B_{min} contours so the confinement of a distribution of alpha particles (not all deeply-trapped) is correlated with the closing of these contours. When $p_2 = 1$, B_{min} contours are not closed in the plasma region and helically-trapped particles drift out of the confinement region. When $p_2 \gg 1$, the configuration appears nearly helically symmetric, B_{min} contours coincide approximately with flux surfaces, and helically-trapped particles are confined. In the case $p_2 \ll 1$ the alpha-particle confinement is not correlated with closing of the B_{min} contours because the majority of trapped particles are trapped by the toroidal $\frac{1}{R}$ variation in B and not by the helical variation. In this case the dominant loss mechanism is stochastic drift¹² of the banana orbits.

The confinement of trapped particles in more complicated magnetic fields can also be explained with the B_{min} model. To illustrate this, trapped particle loss fractions were computed for a variety of torsatron configurations. These configurations differ from the reference reactors in that they have different vertical fields, different helical coil winding trajectories, or $l = 1$ coils in addition to the primary $l = 2$ coil set. Aspect ratios ranging from 3 to 8 and helical ripples ranging from 0.1 to 0.4 were

considered. The results of these calculations are summarized in Fig. 4. The vertical axis is the fraction of trapped particles lost; the horizontal axis is the fractional area f of closed B_{min} contours. The fraction of trapped particles confined can be fitted by

$$f_c = 1.61f^2 \quad f < 0.79 \quad (3a)$$

$$f_c = 1.0 \quad f > 0.79 \quad (3b)$$

with an rms error of only 8% for the wide variety of vacuum configurations considered.

REDUCTION OF DIRECT LOSS FRACTION

The correlation between the area of closed B_{min} contours and the direct loss fraction can be used to study how additional helical harmonics might be added to the single helicity idealized configuration of (Eq. 2) in order to reduce the loss fractions. Flux surfaces are not guaranteed to exist for these model configurations; the results presented here are, however, useful for understanding the tradeoffs available to the stellarator reactor designer.

Mynick¹⁴ proposed poloidal modulation of the helical ripple

$$B(\rho, \theta, \phi) = B_0 \{ 1 - \epsilon_{ia} \rho \cos(\theta) + [1 - \sigma \cos(\theta)] \epsilon_{ha} \rho^2 \cos(6\phi - 2\theta) \} \quad (4)$$

which is the same as (Eq. 2) with ϵ_{ha} replaced by $[1 - \sigma \cos(\theta)] \epsilon_{ha}$. Here σ is an optimization parameter which is chosen to make trapped particle orbits coincide approximately with flux surfaces. Mynick took $p_2 = 1$ and found optimized configurations with $\sigma = 1$. Using the correlation between the B_{min} area and losses, it can be shown that this configuration is a member of a family of zero loss configurations having $\sigma \approx 1/p_2$.

If (Eq. 4) is rewritten in terms of the Fourier expansion (Eq. 1), a spectrum of helical harmonics results. Perhaps a more straightforward way of improving orbit confinement is to add only $l = 1$ and $l = 3$ satellite harmonics to the single helicity configuration. Contours of constant particle loss fraction found with the correlation (Eq. 3) for a configuration having $p_2 = 1$ are shown in Fig. 5. Here p_1 and p_3 are $l = 1$ and $l = 3$ ripple amplitudes normalized to the inverse plasma aspect ratio similar to the definition of p_2 . For single helicity configurations having $p_2 = 1$, the

trapped particle loss fraction is unity. Additional $l = 1$ and $l = 3$ terms reduce the loss fraction to zero in a manner similar to Mynick's σ -optimized configuration. In these configurations, the B_{min} contours coincide approximately with flux surfaces and the configuration appears helically symmetric to helically-trapped particles.

EFFECTS OF FINITE BETA

Vacuum field configurations which approximate the zero loss configurations discussed above can be produced by the ATR-3 coil set by including additional vertical fields to change the shape of the vacuum flux surfaces or shift the magnetic axis inward in major radius. Trapped particle loss fractions can then be reduced to zero. However, Pfirsch-Schluter currents which flow in nonzero-beta plasmas can alter the B spectrum and change particle orbits. To study this effect, three sequences of fixed-boundary zero net current equilibria were obtained with the 3-D code VMEC¹⁴. The initial vacuum field configurations for the three sequences are the standard ATR-3, ATR-3 shifted inward, and ATR-3 with increased central transform. The latter two vacuum configurations have zero losses. The fraction of trapped particles lost versus volume averaged beta is shown in Fig. 6 for the three sequences. The loss fraction increases toward unity with increasing plasma beta. At volume-averaged beta of a few percent, the reduction in losses gained by shifting or shaping the vacuum field flux surfaces has disappeared. This behaviour can also be understood within the context of the B_{min} model. As beta increases and the magnetic axis shifts outward relative to the fixed helical coil set, the B_{min} contours become distorted and noncircular. Even though the area of closed B_{min} contours does not decrease substantially, the center of the B_{min} contours shifts relative to the magnetic axis (Fig. 7). This causes deeply-trapped particle orbits to pass close to the plasma boundary and particles which are not deeply-trapped leave the confinement region. B_{min} contours for two values of plasma beta are shown in Fig. 8 for the inward shifted ATR-3.

The sequence of finite beta equilibria used here are intended to illustrate how finite beta can undo orbit optimization; they are not intended to represent a reactor startup scenario. On-going studies seek to identify startup sequences for ATR-3 which have improved orbit confinement. This ancillary optimization with vertical fields is not effective at improving orbit confinement in the lower aspect ratio ATR-

1 and ATR-2 however. In order to find low aspect-ratio configurations with good orbit confinement, it will be necessary to introduce transport considerations directly into the primary configuration optimization procedure¹⁵.

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Fig. 1. Fraction of alpha particles confined versus radial coordinate for three reference reactors.

Fig. 2. Fraction of alpha particles lost versus pitch angle parameter for ATR-1 and ATR-3.

Fig. 3. Fraction of trapped alpha particles lost versus the ratio of helical ripple to toroidal ripple.

Fig. 4. Fraction of trapped alpha particles confined versus the normalized area of closed B_{mn} contours.

Fig. 5. Contours of constant alpha particle losses for vacuum field stellarator having aspect ratio 5 and helical ripple of 0.2. p_1 and p_3 are $l = 1$ and $l = 3$ ripple amplitudes normalized to the inverse aspect ratio.

Fig. 6. Fraction of trapped alpha particle lost versus volume-averaged beta for three variants of ATR-3. Triangles represent the standard configuration, squares are for a configuration shifted inward in major radius, and circles are for a configuration with increased central transform.

Fig. 7. Variation of the fraction area of closed B_{min} contours and the offset of the B_{min} contours from the magnetic axis with volume-averaged beta for three variants of ATR-3. The symbols denote the same configurations as those in Fig. 6.

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Fig. 8. $B_{\min}$ contours at $\beta = 0$. and $\beta = 3\%$ for the shifted-in ATR-3 configuration. The radial coordinate is proportional to the square root of toroidal flux and the angle variable is Boozer's poloidal angle.