Alpha Particle Heating and Current Drive in FRCs and Spherical Tokamaks

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A Monte Carlo Code [1] is employed to calculate the power deposited in the plasma and the current generated by the α particles produced in D-T fusion reactions. Two types of high beta configurations are considered: Field Reversed Configurations (FRC) [2] and Spherical Tokamaks (ST) [3]. The code follows the exact trajectories (no gyro-averaging) and includes particle drag and pitch angle scattering. The effect of different equilibrium profiles and plasma parameters is studied for both configurations.

Field Reversed Configurations

Field Reversed Configurations are elongated compact toroids with negligible toroidal field. Their aspect ratio is 1 and can reach very high β values (β~1). A relatively small, proof of principle, FRC reactor operating with the D-T fusion reaction has been recently proposed [2]. Alpha particle heating, and its spatial distribution, is a critical issue in the analysis of a fusion reactor. The possibility that the α particles contribute to producing part of the current needed to generate the equilibrium magnetic field must be also analyzed. Here we summarize the results obtained on α particle heating and current drive for a FRC reactor with the parameters proposed in Ref. [2].

The equilibria employed in the calculations are solutions of the Grad-Shafranov equation with a flux dependent pressure of the form:

$$P(\psi) = G_0\left[\frac{\psi}{\psi_0} - \frac{C}{2}\left(\frac{\psi}{\psi_0}\right)^2\right] \tag{1}$$

where G_0 is a constant, ψ_0 is the maximum magnetic flux and C determines the shape of the current profile (hollow for C>0 and peaked for C<0). Since the current produced by the α particles is a small fraction of the total current (see later) its contribution is not included in the equilibrium. In all the calculations it is assumed that the plasma is in a stationary equilibrium, where all parameters remain constant. This means that we assume that the energy deposited by the α particles compensates the losses, which are not calculated.

The Monte Carlo code follows the exact particle orbits in the prescribed equilibria by solving a stochastic equation of the form:

$$\frac{d\mathbf{u}}{dt} = \frac{q}{M}(\mathbf{u}\times\mathbf{B}) - \nu\,\mathbf{u} + \underline{\underline{D}}\cdot\mathbf{u} \tag{2}$$

where q is the charge, M the mass and $\boldsymbol{u}$ the velocity of the particle, $\mathbf{B}$ is the magnetic field and ν and $\underline{\underline{D}}$ are, respectively, the friction and diffusion coefficients of a Brownian particle in velocity space. The isotropic α particle sources are distributed inside the plasma according to the fusion reaction rate.

The parameteres of the different FRC equilibria employed are listed in Table I. B_e is the external magnetic field, n_e the peak electron plasma density, I the total plasma current, r_s and l_s the separatrix radius and length and E the total thermal energy. Deuterium and tritium densities are chosen equal and the temperature of all species is assumed uniform and equal to 10 keV. The current profile is peaked for equilibria E1-E3 and EM (C=-10) and hollow for E4 (C=0.5). EM has magnetic mirrors at both ends.

Several studies have shown that it is possible to form and sustain a FRC with a rotating magnetic field (RMF) [4]. Since the addition of a RMF can increase α particle losses it is important to quantify its effect. This is done by adding to the equilibrium fields a simplified, 1D, analytical representation of the RMF specified by three parameters, the field magnitude outside the separatrix (B_ω), the penetration depth (δ) and the rotation frequency (ω) [5].

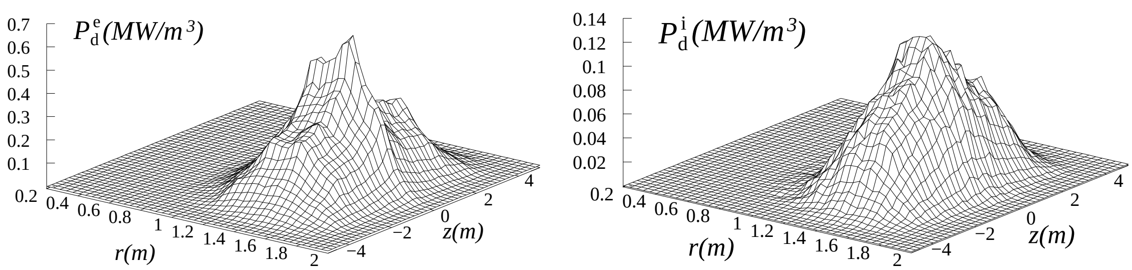

Fig. 1. Power deposited in electrons and ions

The results obtained are listed in Table II. P_g is the α particle power generated and P_d is the power deposited in the plasma, with P_{de} the power deposited in the electrons and P_{di} the power deposited in the ions. I_α is the current generated by the α particles and τ is the energy confinement time that would be needed to sustain the plasma temperature if the α particles were the only heating source. We note that I_α includes only the curent associated to the motion of the α particles. The effective driven current is reduced by electron drag, which is not calculated here. Fig. 1 shows plots of the spatial distribution of the power deposited by the α particles in electrons and ions for an E1 equilibrium.

TABLE I: Equilibrium parameters for FRC reactor

	B_e (T)	n_e ($10^{20}m^{-3}$)	I (MA)	r_s (m)	l_s (m)	E(MJ)
E1	1.3	2.1	16.4	2.0	10.0	41.2
E2	1.83	4.2	23.2	2.0	10.0	84.3
E3	1.3	2.1	15.8	2.8	10.0	79.3
E4	1.3	2.3	24.0	2.0	10.0	81.5
EM	1.27	2.2	12.4	2.0	7.8	40.4

Equilibria E1 (peaked) and E4 (hollow) have the same external field and sepatrix radius but very different values of the produced and deposited powers. These differences can be explained in terms of the total magnetic flux and volumen averaged β of both equilibria. E4 has a high averaged β (0.73) and a low flux (3.77 Wb), resulting in a high power production and a poor α particle confinement. The opposite occurs with E1 which, due to its low averaged β (0.34) and high flux (5.0 Wb), has a lower power production and a better α particle confinement. The fraction of power deposited in the plasma is large for E1, E2, E3 and EM but the current generated is very small. In all the cases the power deposited in the electrons is approximately four times larger than the power deposited in the ions.

Table II: Results for the equilibria of Table I.

	$P_g(MW)$	$P_d(MW)$	$P_{de}(MW)$	$P_{di}(MW)$	$P_d/P_g(\%)$	$I_\alpha(MA)$	$\tau(s)$
E1	16.5	12.2	10.0	2.2	73.9	0.25	3.45
E2	66.0	59.3	48.2	11.1	89.8	0.41	1.42
E3	30.1	26.7	21.7	5.0	88.7	0.28	2.96
E4	41.8	18.2	14.9	3.3	43.6	0.44	4.46
EM	16.2	13.9	11.1	2.8	86.1	0.23	2.89

Comparing the results for E1 and E2 it is clear that increasing the density (and the external magnetic field) would be benefical in terms of the required energy confinement time, because the generated fusion power increases by a factor 4 and the fraction of power deposited (as percentage of the total) also increases. The problem is that the beam current drive efficiency decreases and there could be too much wall loading. A comparision between E1 and EM, that have basically the same density and external field, shows that adding mirrors results in a significant increase in the deposited power fraction. Finally, increasing the radius by a factor √2 increases the deposited power fraction by approximately the same amount as adding mirrors.

We studied the effect of a RMF. In Fig. 2 we can see the power deposited by the α particles for an E1 equilibrium as a function of the RMF frequency for B_ω = 100 Gauss and B_ω = 50 Gauss. The power deposited is lower than in the case without RMF because the RMF deteriorates the confinement. There is a broad minimum but no sharp resonances.

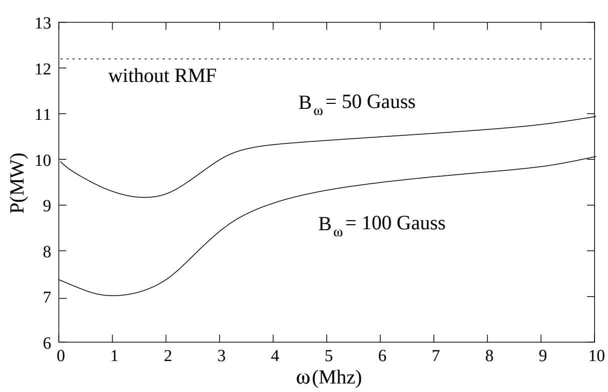

Fig. 2. Power deposited as a function of the RMF frequency; δ=0.1 r_s

Spherical Tokamaks

The loss of energetic α particles can seriously degrade the performance of a D-T fusion reactor. In addition, if the lost particles concentrate in a small region, they can damage the first wall and release impurities. We calculated the magnitude and spatial distribution of the power deposited by the α particles in electrons and ions and determined the position and velocity of the escaping particles.

The boostrap current driven by fusion produced α particles can contribute to the total current in tokamak reactors. In addition to this current, a neoclassical current caused by the asymmetry in the boundary between passing and trapped particles (the number of passing particles with velocity in the same sense as the current is somewhat larger than the number of passing particles moving in the opposite sense) has been found [6]. Tani and Azumi [7] recently employed a Monte Carlo code to study current generation by α particles in ITER and a relatively small aspect ratio (A=2) tokamak. In this code the guiding-center equations are integrated numerically and collisional effects included with a Trubnikov type collision operator.

Using the guiding-center equations is probably justified in large aspect ratio, high field, tokamaks but not in STs. In a ST reactor with the parameters given in Ref. [3], the Larmor radius is of the same order as the banana width and $a/\rho\sim 0.05$, where a is the minor radius and ρ the Larmor radius. In this situation, using the exact particle trajectories could produce significantly different results. We employed the Monte Carlo code described in the previous section to calculate the current generated by the α particles and the power they deposit in the plasma for ST reactors.

Two types of plasma equilibria and three different values of the aspect ratio were employed. The first type of equilibrium considered is a simple analytical solution of the Grad-Shafranov equation (Solov'ev equilibrium) [8] while the second one is a numerical solution obtained by using the same pressure dependence as in Eq. (1) and a poloidal current of the form:

$$I_p(\psi) = I_0 + I_1\left(\frac{\psi}{\psi_0}\right) \tag{3}$$

The main plasma parameteres of the different equilibria, which were taken to be similar to those in Ref. [3], are listed in Table III. S1-S3 are Solov'ev equilibria while E1-E3 are numerical solutions of the G-S equation with C=-8 (hollow).

TABLE III: Equilibrium parameters for ST reactors

	A	$R(m)$	$a(m)$	κ(95%)	q_0	q_{95}	I (MA)	B_e (T)	n_e ($10^{20}m^{-3}$)	E(MJ)
S1	1.4	2.8	2	3.48	2.03	12.05	27.8	2.2	1.71	471.0
E1	1.4	2.8	2	3.45	2.54	9.93	30.3	2.14	1.61	409.3
S2	1.6	3.2	2	3.47	1.90	7.0	28.0	2.14	1.61	524.8
E2	1.6	3.2	2	3.46	2.03	7.0	28.6	2.14	1.59	457.2
S3	1.8	3.6	2	3.51	2.0	6.5	28.0	2.14	1.59	553.8
E3	1.8	3.6	2	3.45	2.51	6.0	27.9	2.14	1.59	507.4

A is the aspect ratio, *R* and *a* the major and minor radii respectively, κ the elongation (at the 95% flux surface), q_0 and q_{95} the safety factor at the magnetic axis and 95% flux surface respectively, *I* the toroidal plasma current, n_e the peak electron density and *E* the energy content of the plasma. Fig. 3 shows the *q* profiles of equilibria E1-E3 and S1-S3.

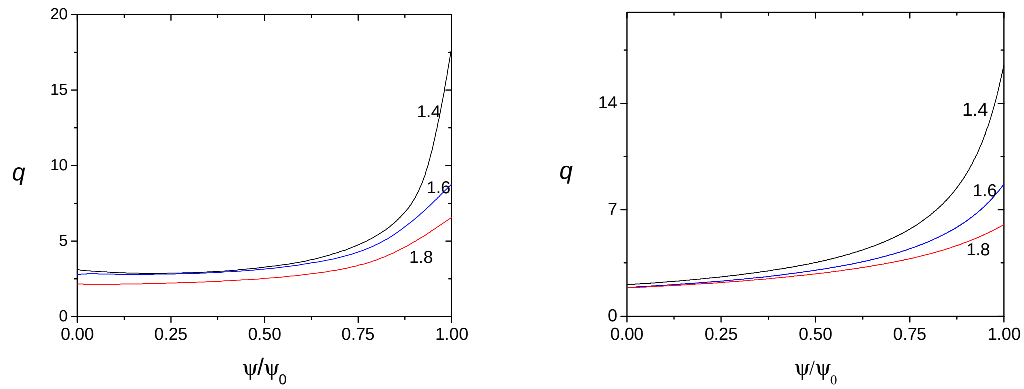

Fig. 3. *q* profiles, as a function of poloidal flux, for different aspect ratios. Left E1-E3, right S1-S3

The results are summarized in Table IV. The first 7 columns of this Table contain the same quantities as in Table III. The last two columns contain the fractions of prompt losses (particles lost before colliding) and particles that become thermalized inside the plasma.

Table IV: Results for the equilibria of Table III.

	$P_g(MW)$	$P_d(MW)$	$P_{de}(MW)$	$P_{di}(MW)$	P_d/P_g	$I_\alpha(MA)$	$\tau(s)$	*Prp. (%)*	*Term(%)*
S1	251.5	246.7	178.0	68.7	0.981	1.1	1.87	1.0	88.0
E1	184.8	177.5	128.7	48.8	0.960	1.39	2.3	0.0	82.7
S2	264.6	258	186.0	72.0	0.975	1.12	1.98	2.3	86.4
E2	204.8	193.8	141.1	52.7	0.946	1.17	2.36	0.1	80.4
S3	328.1	317.7	228.7	88.9	0.968	1.13	1.74	3.9	88.0
E3	225.8	214.0	156.0	58.0	0.947	1.14	2.37	0.0	80.3

Fig. 4 shows the spatial distribution of the power deposited in electrons and ions for an S2 equilibrium. The deposited power has a maximum at the magnetic axis for both species. The power deposited in the electrons is approximately 2.5 times larger than the one deposited in the ions. The spatial distribution of lost particles is fairly uniform, with more particles lost on the low field side but without localized "hot" spots. The deposited power fraction is large for all the S-type equilibria and increases when the aspect ratio is reduced. This increase is probably related to the reduction of prompt losses, from 3.9 % for *A*=1.8 to 1.0% for *A*=1.4. E-type equilibria have fewer prompt losses but the deposited power fraction is smaller than for S-type equilibria of the same aspect ratio. This indicates that the deposited power is rather sensitive to the details of the equilibrium and that an accurate determination of the power deposited by α particles in a ST reactor requires a precise, self consistent, calculation of the equilibrium profiles

The current produced by the α particles is a small fraction of the total current. Fig. 5 presents the spatial distribution of the α particle current density showing the existence of positive and negative regions. The negative region near the magnetic axis is due to trapped particles. This is seen more clearly in Fig. 6 which shows the spatial distribution of the current density due to trapped particles. Fig. 7 shows a radial profile of the total α particle current density and the contribution of trapped particles. The difference between both curves is the current produced by circulating particles.

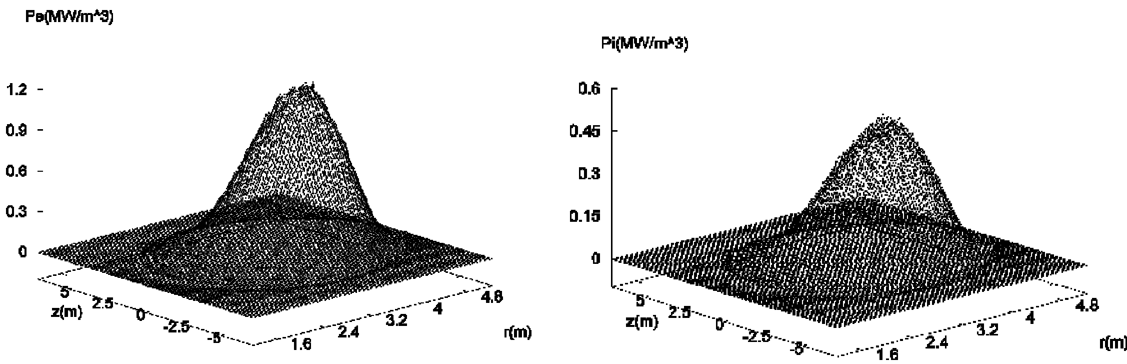

Fig. 4. Power deposited in electrons and iones for an S2 equilibrium.

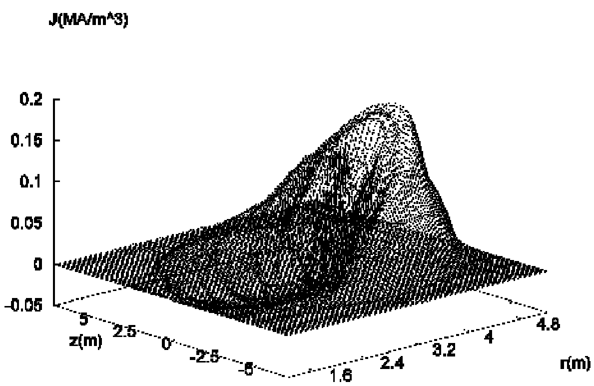

Fig. 5. Spatial distribution of current density

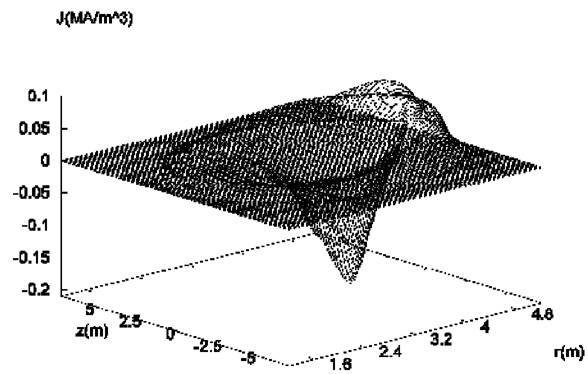

Fig. 6. Trapped particles current density

The radial profile of the current density presents an oscilatory behavior. Although the origin of these oscillations is not clear at this time we note that their period is comparable to the size of the α particle orbits. The contribution of the trapped particles is negative near the magnetic axis (r_m=3.78) and positive in the low field side. A similar behavior was found in Ref. [7].

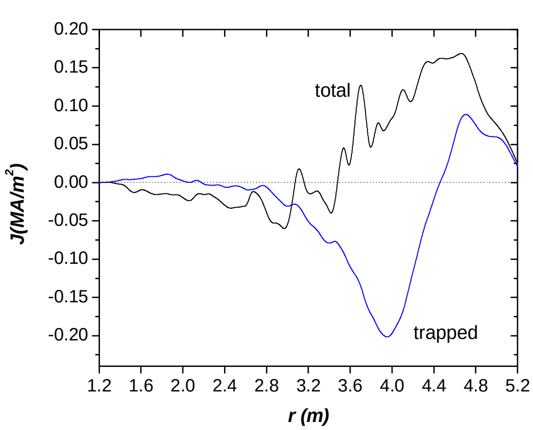

Fig. 7. Radial profile of J_α

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