

## Current Drive and Heating in a D-<sup>3</sup>He FRC Fusion Reactor

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The Field Reversed Configuration (FRC) is a natural candidate to operate with advanced fuels (i. e. D-<sup>3</sup>He) due to its high  $\beta$  value. We study several methods that have been proposed to sustain fusion conditions in a D-<sup>3</sup>He FRC reactor. The most important one uses the protons and  $\alpha$  particles of the fusion reactions, which can contribute to the current and heat the plasma [1]. Other mechanisms are Neutral Beam Injection (NBI) [2] and Rotating Magnetic Fields (RMF). We analyze the ARTEMIS project [3], a D-<sup>3</sup>He FRC conceptual reactor design. The basic parameters are:  $T_i = T_e = 87.5$  keV,  $B_e = 6.7$  T (external magnetic field),  $r_s = 1.12$  m,  $2z_s = 17$  m. (separatrix radius and length)

### Current drive and heating by fusion protons and $\alpha$ particles

We consider three different equilibria. Two are numerical solutions of the Grad-Shafranov equation, with E1 peaked and E2 hollow, and the other (E3) is an improved Hill's vortex [4]. Equilibrium parameters are listed in table 1.

	$n_a$ ( $10^{20} m^{-3}$ )	$P_p$ (MW)	$P_\alpha$ (MW)	$E_t$ (MJ)	$\beta$
E1	3.2	336.5	83.8	823.5	0.44
E2	5.5	766.8	190.9	1427	0.75
E3	3.1	330.1	82.2	792.9	0.42

Table 1: Equilibrium parameters.

where:  $n_a$  is the average electron density,  $P_p$  is the total proton power generated,  $P_\alpha$  is the total  $\alpha$  particle power generated,  $E_t$  is the total thermal energy of the plasma, and  $\beta$  is defined as:  $\beta = V^{-1} \int p dV / (B_e^2 / 2\mu_0)$ .

The numerical code employed in this study has been described elsewhere [1,2]. It follows the exact particle trajectories and introduces Coulomb collisions via a Fokker-Planck type collision operator that includes particle drag and pitch angle scattering. To simulate the effect of isotropic proton (14.7 MeV) and  $\alpha$  particle (3.7 MeV) sources we distribute the fluxes produced at each point over a large number of directions, that span the  $4\pi$  radians.

The results obtained for the three equilibria considered are summarized in table 2, which shows the total proton ( $I_p$ ) and  $\alpha$  particle ( $I_\alpha$ ) currents, the power deposited by the protons ( $P_p^d$ ) and the  $\alpha$  particles ( $P_\alpha^d$ ), the total deposited power ( $P_t$ ) and the global energy confinement time

that would be needed to sustain the plasma temperature ( $\tau_E = E_t/P_t$ ).

Figs. 1 and 2 show of the proton and  $\alpha$  particle current density profiles obtained for E1. The currents are 39.4 MA for the protons (close to the value quoted in [3]) and 1.63 MA for the  $\alpha$  particles. Fig. 3 shows the spatial distribution of the power deposited by the protons in the background plasma for an E1 equilibrium.

	$I_p(\text{MA})$	$I_\alpha(\text{MA})$	$P_p^d(\text{MW})$	$P_\alpha^d(\text{MW})$	$P_t(\text{MW})$	$\tau_E(\text{s})$
E1	39.4	1.6	118.0	70.5	188.5	4.36
E2	34.8	2.9	95.8	58.3	154.1	9.2
E3	46.6	1.8	153.9	54.3	208.1	3.8

Table 2: Calculated quantities.

The fraction of proton power deposited in the plasma is small and shows a strong dependence on the shape of the equilibrium. An analysis of the proton losses indicates that most protons escape through the ends of the configuration. The addition of magnetic mirrors at both ends should improve proton confinement and reduce the required energy confinement time. Although the generated  $\alpha$  particle power is only 20% of the total, its contribution to the deposited power is significantly larger because they are better confined.

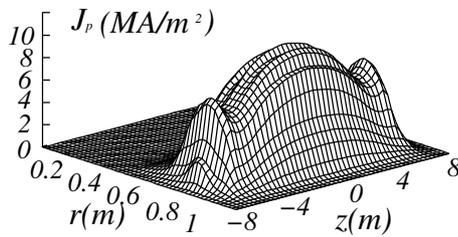


Fig. 1: Proton current profile.

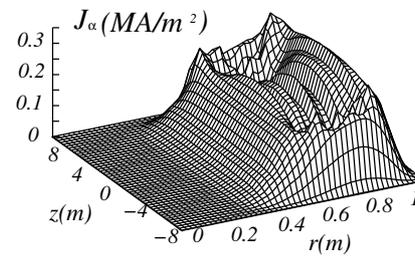


Fig. 2:  $\alpha$  particle current profile

## Neutral Beam Injection

In the ARTEMIS design [3] it is assumed that part of the current (8 MA) will be sustained by 5 A of 1 MeV neutral beams. We use the same code as in the previous section, with an ionization package, to study the interaction of the beam with the plasma. The particles are neutral at the injection point and the code calculates their ionization, stopping and thermalization. The maximum current that could be driven by the beam can be estimated by considering a field free plasma with uniform density and using the dielectric approximation to model the effect of the plasma on the beam stopping. This gives a current of  $\sim 1.3$  MA, much lower than the ARTEMIS estimation. A substantially larger, but incorrect, beam current ( $\sim 6$  MA) is obtained employing

a constant collision frequency calculated using the initial velocity of the beam particles. This could explain the value quoted in [3].

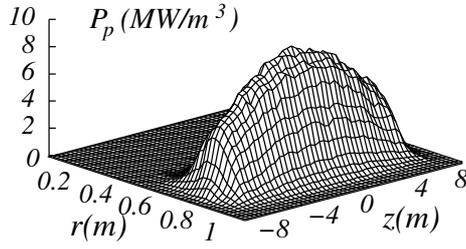


Fig. 3: Proton power deposited.

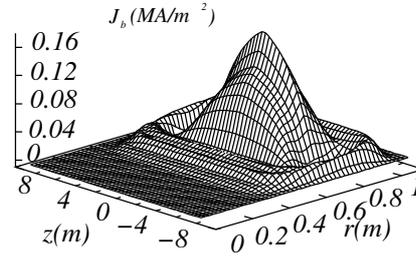


Fig. 4: Beam current profile.

The current calculated with the code is 0.32 MA. In Fig. 4 we show the beam current density profile. There are three reasons that explain why the current calculated with the code is lower than the theoretical value. The first one is that a fraction of the ionized particles, approximately 18% for E1, is lost through the ends of the configuration before becoming thermalized. The second one is that due to the particular magnetic field structure of FRCs, particles ionized close to the separatrix end up rotating around the FRC axis in the counter current sense (it could be as high as half of the particles). The third one is that due to the low beam energy most particles have orbits with large radial oscillations and relatively small azimuthal velocity while circular orbits are assumed in the theoretical calculation.

Since many of the effects that reduce the current drive efficiency, such as the number of particles rotating in the counter current sense, do not depend on Coulomb collisions it is possible to analyze the importance of these effects, and search for plasma parameters that result in higher efficiencies, without employing too much computing time. After a detailed analysis we identified a set of parameters close to the original ones that resulted in a significantly larger beam current. Using  $r_s = 1.06$  m,  $B_e = 6.4$  T and  $E_n = 1.2$  MeV and the other parameters as before we obtained a beam current of 0.95 MA.

### Rotating Magnetic Fields

Several theoretical and experimental studies [5] show that it is possible to form and sustain a FRC with a RMF. The RMF can penetrate into the plasma when a fraction of the electrons rotate synchronously with the RMF. This is possible when  $\gamma > \lambda$ , where  $\gamma = eB_\omega/m_e v$  measures the strength of the RMF and  $\lambda^2 = a^2 \mu_0 \omega n e^2 / 2m_e v$  is the ratio of the plasma radius to the skin depth. The RMF acts mostly on the electrons.

Since the addition of a RMF to a 2D equilibrium can increase particle losses we study the effect of the RMF on the fusion protons. An analytical fit to the RMF field is employed [5]. Three parameters are needed to specify the RMF, the field amplitude  $B_\omega$ , the rotation frequency

$\omega$  and the penetration depth  $\delta$ . We use  $\delta = 0.1r_s$ ,  $B_\omega \sim 0.01T$  and  $\omega \sim 1 \times 10^5$  1/s. In Fig. 5 we show the total proton current as a function of  $B_\omega$  and in Fig. 6 the total proton current as a function of  $\omega$ . A clear reduction of the proton current is observed when the RMF is introduced. It remains to be seen if the current driven by the RMF (not calculated here) can outweigh the reduction of the proton current.

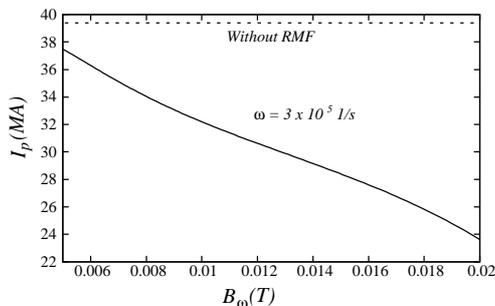


Fig. 5: Proton current as a function of RMF amplitude

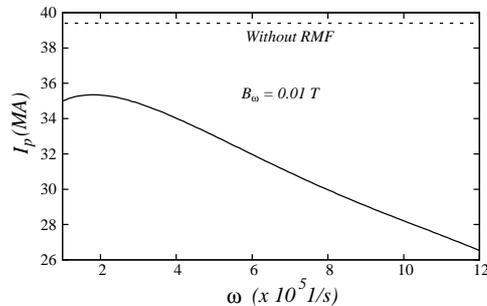


Fig. 6: Proton current as a function of RMF frequency

## Summary and conclusions

We studied various methods to sustain the current and heat the plasma in a  $D-^3\text{He}$  FRC reactor. Unlike previous studies, the effect of collisional diffusion and plasma equilibrium were analyzed. It was found that both the generated current and the fraction of power deposited in the plasma are quite sensitive to the shape of the equilibrium and to diffusion. Due to the particular magnetic field structure of FRCs a fraction of the energetic particles (protons,  $\alpha$  particles, beam ions) rotate in the counter current sense, thus reducing the total current. The inclusion of diffusion increases significantly the loss of these particles.

The total proton current could reach the values required in the ARTEMIS project but it seems difficult to simultaneously achieve high fusion power and good confinement. In the parameter range considered NBI does not seem to be an efficient current drive method.

The addition of a RMF reduces the proton current. It is necessary to determine if the current driven by the RMF outweighs the reduction in the proton current and provides additional control on the total current profile.

## References

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