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Numerical Calculations of Neutral Beam Injection in FRCs and Spheromaks

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1 General remarks

Neutral beam injection (NBI) has been routinely used to heat the plasma in Tokamaks, and several experiments have demonstrated the possibility of using beams to drive a significant fraction of the plasma current [1]. In compact toroids, some preliminary theoretical studies on NBI have been done [2], and experimental activities started recently [3].

We employ a Monte-Carlo code [4] to study NBI current drive and heating in Field Reversed Configurations (FRCs) and Spheromaks. The code calculates the ionization of the neutral atoms and follows the exact trajectories of the ions (no gyro-averaging). Guiding-center equations fail to describe the trajectories of the energetic beam particles in these high-β toroids [5].

The magnetic field and pressure profiles are determined self-consistently by solving the Grad-Shafranov equation with additional terms corresponding to the beam current. The hollowness parameter D, which relates the flux to the plasma pressure, allows to specify the type of equilibrium [6] (peaked-elliptical equilibria for $D<0$ and hollow-racetrack for $D>0$). In FRCs, which do not have toroidal field, the value of D has a strong effect over the beam distribution. The equation is solved inside the separatrix, which is a cylindrical surface of radius r_s and height Z_s. The beam is injected at the midplane (z=0), with "impact parameter" b (distance to the plasma geometrical axis). Setting the values of the neutral injection current (I_N) and the energy of the beam particles (E_N), the beam is completely specified.

2 Field Reversed Configuration

The plasma parameters are r_s=30 cm, z_s= 240 cm, magnetic axis radius r_0=21 cm, $n \approx$ 0.8-1.4 10^{15} cm^{-3}, T_e=T_i=0.5 keV and B_{ext}= 5 kG. Fig. 1 shows the spatial distribution of beam current for peaked equilibria (D=-10) and hollow equilibria (D=0.5). The beam, injected perpendicularly to the FRC axis at the midplane, spreads over all the length of the plasma due to diffusion produced by collisions with the plasma ions. At low currents (Figs. 1.a-1.b),

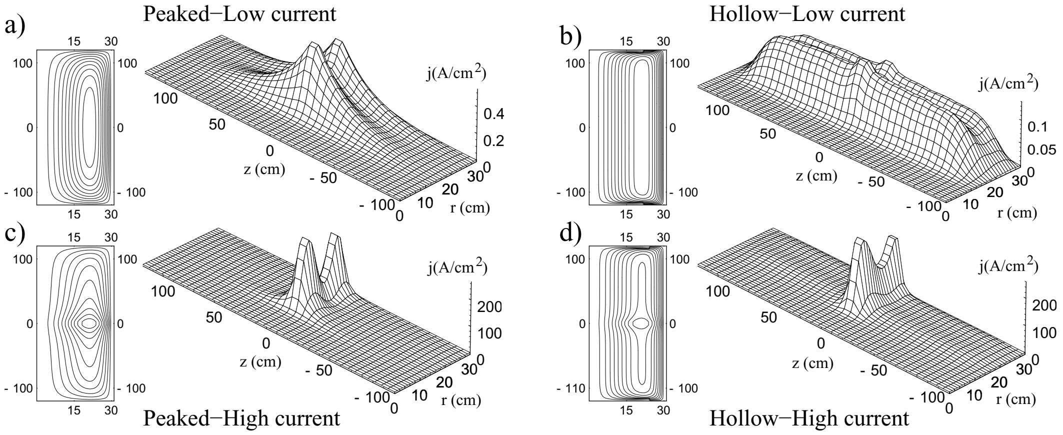

Figure 1: Flux surfaces and beam current spatial distribution for peaked and hollow equilibria and low (I_N=1 A) and high (I_N=300 A) beam currents. E_N=20 keV.

when the equilibrium is hardly distorted, the beam is more concentrated in the peaked than in the hollow case, due to the larger magnetic flux gradient near the midplane of the former. In all the cases, the beam current has a double-peaked radial profile. This structure is a general characteristic of beam currents in FRC devices, and is due to the radial oscillation of the beam particles around the magnetic null (betatron orbits).

High current beams have an important effect on the high-β FRC equilibria (Figs. 1.c-1.d). The beam current increases the magnetic field near the injection region, producing a self-confining effect which reduces the axial excursions of the deflected beam ions. This effect is also found for injection off-midplane and for beams with finite area.

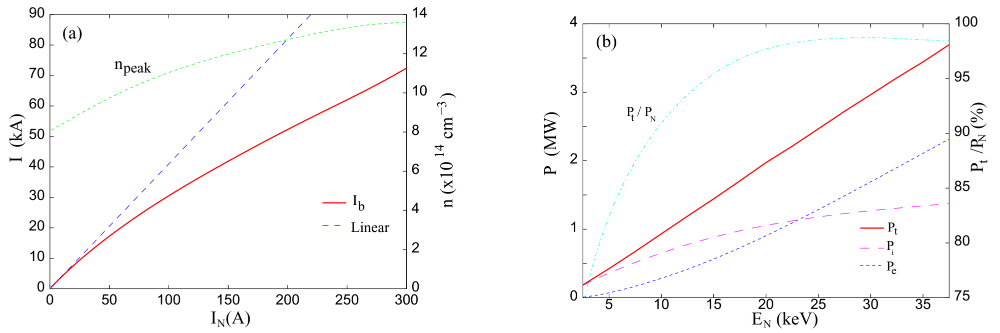

Figure 2: (a) Beam current and plasma peak density vs. I_N and (b) deposited power vs. E_N (absolute and fraction of injected). D=-10.

Due to the high-β of FRCs (β ≈ 1), the increase in the magnetic field around the injection region at high beam current produces a similar increase in the density. Fig. 2.a shows that the peak plasma density rises with I_N, and therefore the increase in the beam current is slower than linear.

At low energies, a reduction in the fraction of trapped beam particles, and therefore of the deposited power, is found (Fig. 2.b). This behavior can be explained by noting that when the energy is low, a considerable fraction of the particles ionizes far from the null. These particles are trapped in non-crossing orbits, and in most cases end-up leaving the system through the ends.

3 Spheromak

The plasma parameters are D=0.5, r_s=z_s= 50 cm, r_0=31 cm, $n \approx 10^{14}$ cm^{-3}, T_e=T_i=0.5 keV and B_{ext}= 7 kG. The current driven by the beam is the beam current minus the electron canceling current [7] which is due to drag of plasma electrons by the beam (unlike FRCs, in Spheromaks a fraction of the electrons circulates in the toroidal direction). The maximum cancelation occurs at the magnetic axis, where there are no electrons trapped in banana-like orbits. Fig. 3 shows the current carried by the beam and the total driven current, i. e.

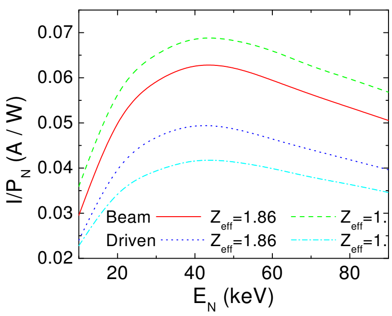

Figure 3: Beam and driven current vs. E_N. I_N=40 A, b=31 cm.

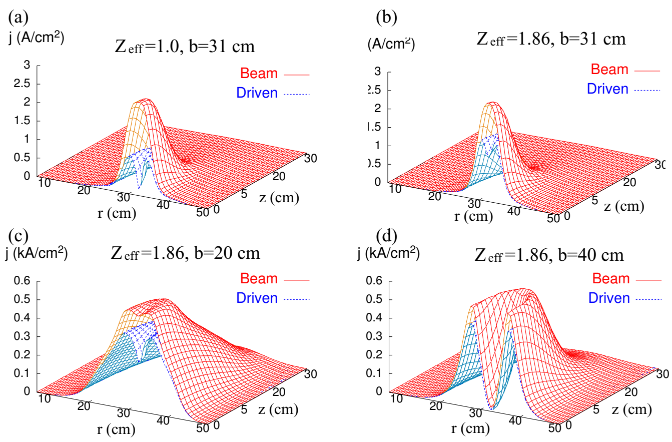

Figure 4: Spatial distribution of beam and driven current density for Z_{eff}=1 and 1.86, and selected values of b. E_n= 90 keV, I_N=40 A.

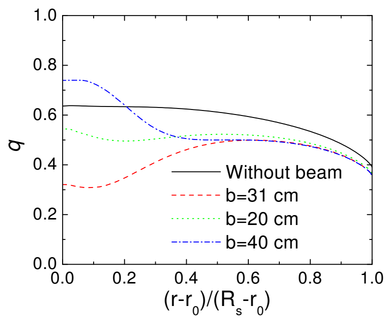

Figure 5: Safety factor radial profile for selected values of b. E_N=50 keV, I_N=40 A, Z_{eff}=1.86

beam current minus electron canceling current, per unit of injected power. The curves for Z_{eff}=1 and Z_{eff}=1.86 are displayed. The current presents a broad maximum around 40 keV.

The beam current is higher for Z_{eff}=1 than for Z_{eff}=1.86, but the total driven current is lower in the former case. The reduction of the plasma effective charge does not result in an improvement in the total current drive efficiency because the reduction of the stopping cross section is compensated by an increase in the electron canceling current.

Beam current profiles are broad for injection with $b < r_0$, concentrated around the magnetic axis for $b \approx r_0$ and hollow for $b > r_0$ (Fig. 4). The electron canceling current is larger for $b \approx r_0$, because the beam concentrates in the region with smallest fraction of trapped electrons. For low Z_{eff}, the electron canceling current is almost half the beam current.

The safety factor profiles of the self-consistent equilibria show a clear sensitivity to the impact parameter (Fig. 5). When $b > r_0$, the current concentrates around the axis thus reducing q_0. When $b > r_0$, the hollow current profile increases q_0. Finally, when $b < r_0$ there is a small reduction in q. The power deposition distribution can be controlled even with the simple injection geometries employed here, where only b is allowed to change. When beams are injected below the magnetic axis ($b < r_0$), the power is deposited over a broad region that becomes more concentrated around the axis as b approaches to r_0. For $b > r_0$ the profile is hollow, i.e. the power deposited at the plasma core is small.

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