Plasma current and rotation generated by fast beam ions, and bootstrap current in a compact high field spherical tokamak.

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Abstract. Codes NFREYA, NFIFPC and TORUS II are used to calculate current driven due to the Neutral Beam Injection, as well as torque and power deposition, the rotation speed and the bootstrap current in ST40 high field spherical tokamak. We show that for ST40 conditions, the value of the Neutral Beam driven current is much smaller than the bootstrap current. Using the torque deposition profile calculated by NFREYA, the velocity profile and the shearing rate are computed and compared with the growth rate of the ITG (Ion Temperature Gradient) instability.

1. Introduction

The new generation high field spherical tokamak ST40 (R_0=0.4m, A=1.8, I_{pl}=2 MA, B_t=3 T, k=2.5) is under construction by Tokamak Energy Ltd, UK. The current drive, produced by the Neutral Beam Injection (NBI), bootstrap current, torque from NBI and resulted plasma rotation have been investigated with the Monte Carlo code NFREYA/1/, NFIFPC (New Fast Ion Fokker - Planck code) /1/ and the 1.5d-transport code TORUS II /2/. During slowing down /3/ the injected fast ions deposit power and torque which produces plasma heating and rotation /4/. It has been already shown /5/ that heating of the plasma may increase bootstrap current fraction /6,7/ and so drive current in much more efficient way than direct NB current drive. Here we demonstrate this for a particular case of ST40. Increase in the plasma toroidal rotation can improve the confinement due to suppression of some turbulences by the velocity shear /8/, thus the shearing rate is compared with growth rate of the ITG and the DTEM (dissipative trapped electron mode) instabilities /9,10/.

2. Slowing down, torque, rotation, NBI driven and bootstrap current

The slowing down of the injected fast ions due to the background plasma can be described by the Fokker - Planck equation. This equation allows to compute the distribution function of the fast particles in the velocity space. Numerical methods, e. g. finite differencing used in NFIFPC or Monte - Carlo (M-C) simulations as in NFREYA are applied. Assuming that the particle tracks are independent, a M–C approach is possible /11/. In NFIFPC, which accounts for the ion – ion interaction as well, the current density is obtained by solving the Fokker – Planck equation for up to 15 radial sheaths. The bootstrap current is calculated following /3,4/ with corrections for the ST geometry /4,5/.

Assuming that the plasma in ψ-$\psi+\Delta\psi$ sheath rotates with the same angular velocity ω, we obtain for the mean rotation speed $v_\phi(r)=R_o\omega(r)$ a transport equation /4/ which is included in the 1.5 d code TORUS II /2/.

As mentioned above, the rotation (velocity shear) can improve the confinement by suppressing the ITG, DTEM and other instabilities. We compare the Hahm–Burrell shearing rate /8/ which is approximately given by $\Omega_{ExB}= B_{pol}/B_{tor}\ (dv_\phi/dr)$, with the growth rates of different instabilities, ITG ($\gamma_{ITG,C}$ /9/, $\gamma_{ITG,T}$ /10/) and DTEM (γ_{DTEM} /10/).

3. Results

Table 1 shows results of calculations of the NB driven current and the torque for ST40 with the background plasmas characterized by the maximum temperatures T_{e0}=4.3 keV,T_{i0}=5.4 keV and by T_{e0}= 7 keV, T_{i0}=10 keV, and the maximum electron density n_{e0}=1.5 10^{14}/cm^3.

Table 1

	Beam energy E_b=40 keV			Beam energy E_b=70 keV		
T_{i0} / T_{e0}	5.4/5.3keV	10/7keV	10/7keV	5.4/5.3keV	10/7keV	10/7keV
R_b[cm]	J_{CD}[kA]	J_{CD}[kA]	T[Nm]	J_{CD}[kA]	J_{CD}[kA]	T[Nm]
40	85	80	0.72	138	150	0.81
47.5	96	93	0.81	145	154	0.87
55	111	104	0.92	171	174	1.12

The beam energy E_b is either 40 or 70keV and the beam power P_b is 1MW. Both the driven current and the torque increase with the beam tangency radius R_b, and with the beam energy. At higher beam energy (70 keV) the deposited torque increases roughly by 15%.

Fig. 1 shows the distribution of the boostrap current density (NBI power P_b=1MW, NB energy E_b = 40keV). The dependence of the bootstrap fraction f_{bs} (Fig. 2) on T_i shows that at T_i~ 9.2 keV the bootstrap fraction f_{bs}= 0.85 can be reached. The estimate of f_{bs} from the Hoang's scaling, S, /see reference in 7/ is also shown for different density profiles, n_e ~ 1-(r/a)^n with n = 1 and 2. The poloidal β_p reaches 1.2 at the density n_e = 2x10^{14}cm^{-3}. Fig 3 shows the time evolution of the toroidal ion speed which saturates at 500 km/sec. An empirical model was used here for the viscosity and heat diffusivities to agree approximately with those in /12/. The ion temperature (Fig. 4) reaches 11 keV. The Hahm-Burrell shearing rate /8/ (Fig.5) is smaller than $\gamma_{ITG,T}$ by a factor ~3 and smaller than $\gamma_{ITG,C}$ by a factor ~5. However, the estimate k*ρ ~1 in /9/ and k*ρ ~0.5 in /10/ (k is the parallel wave vector and ρ is the Larmor radius) is only an order of magnitude estimate so that a stabilizing effect of the rotation cannot be excluded. For E_b = 70keV, the slowing down orbit of a 70 keV injected ion (Fig.6) encircles the right stagnation point where the ion thermalize. The movement to the stagnation point is due to the energy loss at each collision. Pitch angle scattering in ST40 does not change the orbit topology, what typically is not the case for counter running particles at high aspect ratio. The velocity distribution function (Fig.7) at the plasma center is dominated by the 70keV component because the other 35 keV and 23 keV components of the injected ions (1 MW, 40 keV NBI with 59% D+, 22% D+2, 19% D+3), are far below the critical energy. However at the plasma boundary, Fig.8, all components are well above the critical energy and so contribute to the distribution and to the driven current. This effect should be taken into account when calculating the total deposition.

4. Conclusions

To obtain 2 MA plasma current in ST40, NBI may be used generating a seed current of around 170 kA and a bootstrap current of around 1.7 MA, so the regime is close to fully non-inductive. The needed extra current can be provided by a small solenoid, which will be installed on ST40, or by other current drive schemes (RF, microwave). The concomitant rotation may improve the confinement so that higher temperatures may be reached thus increasing the bootstrap fraction.

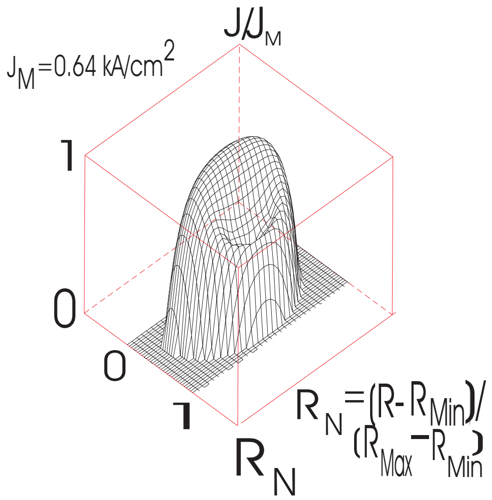

Fig.1 2d-bootstrap current density

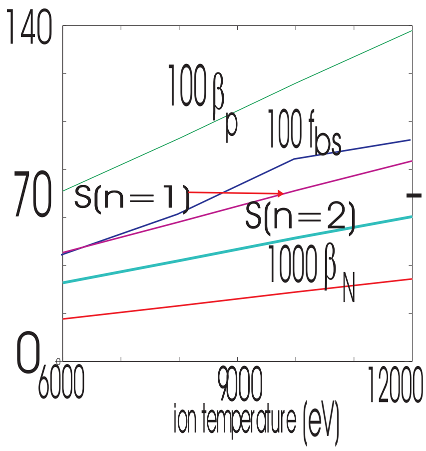

Fig.2 Dependence of f_{bs}, β_p, β_N and S on T_i

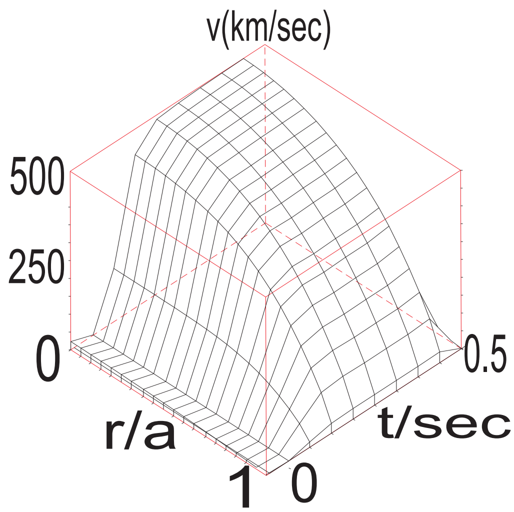

Fig.3 Evolution of the toroidal ion speed

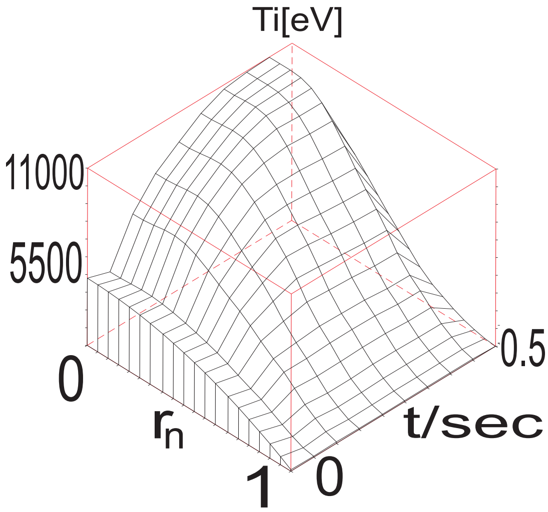

Fig.4 Evolution of the ion temperature

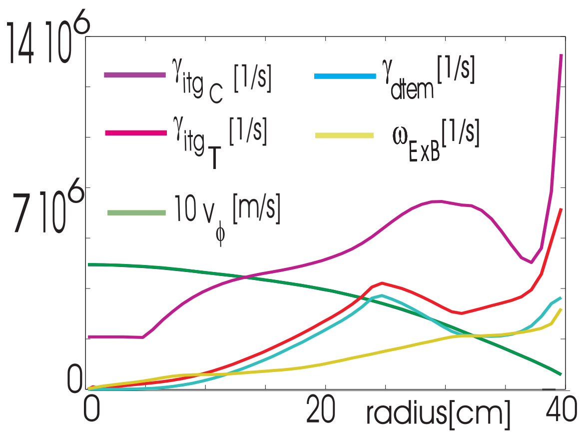

Fig.5 Shearing rate ω_{ExB}, ITG growth rates, DTEM growth rate, toroidal speed v_ϕ

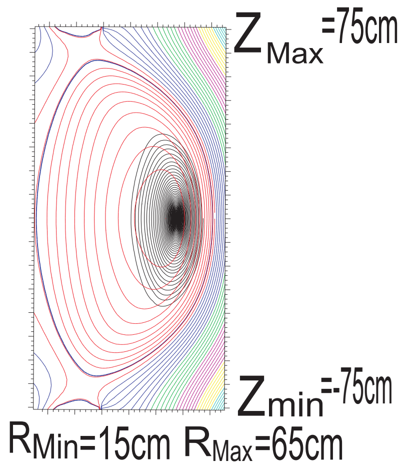

Fig.6 Slowing down orbit contracting around the right stagnation point

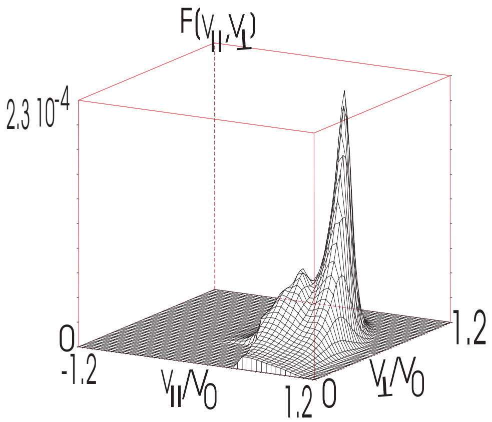

Fig.7 Fast ion distribution at the plasma center

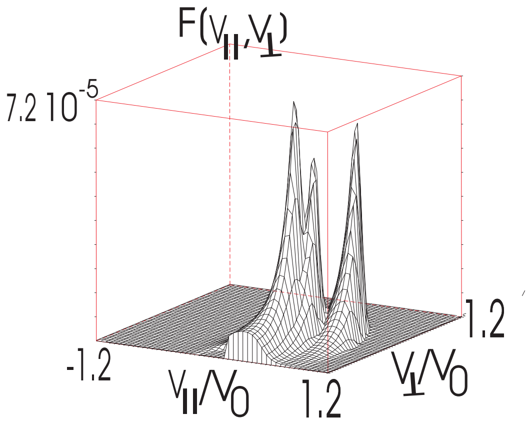

Fig.8 Fast ion distribution at the plasma boundary

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