Calculation of the bootstrap current profile for the stellarator TJ-II

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Introduction

The control of the bootstrap current [1] may lead to the possibility of continuous operation in tokamak overdense plasmas. In stellarators, it can provide access to improved confinement regimes, by means of control of the rotational transform profile. On the other hand, since stellarators are aimed to be currentless devices, the bootstrap current may perturb the magnetic configuration produced by the coils. This is specially important for shearless devices, such as the heliac TJ-II. Indeed, one of the main lines of research at TJ-II is the relation between confinement and the magnetic configuration [2]. Therefore, an estimation of finite-β effects on issues such as the rotational transform profile, the presence of rational surfaces or the magnetic well, is of great importance.

The bootstrap current is a neoclassical effect triggered by the radial gradients of the density and temperature in the presence of an inhomogeneous magnetic field. In order to estimate the bootstrap current, one has to solve the Drift Kinetic Equation (DKE):

$$\left(\frac{\partial}{\partial t}+\mathbf{v}_\mathrm{g}\cdot\nabla-\mathscr{L}_\mathrm{c}\right)\hat{f}=\mathbf{v}_\mathrm{g}\cdot\nabla\psi\,,\quad f=f_\mathrm{M}-\hat{f}\frac{\partial f_\mathrm{M}}{\partial\psi}\,, \tag{1}$$

where $\mathbf{v}_\mathrm{g}$ is the guiding center drift velocity, ψ is the radial magnetic flux coordinate and $\mathscr{L}_\mathrm{c}$ is the Lorentz collision operator. $\hat{f}$ is the normalized perturbation of the distribution function f and it is defined through the local Maxwellian one-particle distribution function f_M. Eq. (1) is linear in $\hat{f}$ and local. Under these assumptions, the fluxes can be expressed as linear combinations of the gradients of density and temperature and of the electric field. For each specie b:

$$j_\mathrm{b}=-en_\mathrm{b}\left(D_{31}^\mathrm{b}\left(\frac{\mathrm{d}ln n_\mathrm{b}}{\mathrm{d}r}-q_\mathrm{b}\frac{E_\mathrm{r}}{T_\mathrm{b}}\right)+D_{32}^{b}\frac{\mathrm{d}lnT_\mathrm{b}}{\mathrm{d}r}\right)\,. \tag{2}$$

As usual, T_b and n_b denote temperature and density, and E_r is the radial electric field. The electric charge is q_b, b = e are electrons and b = i protons. The brackets denote volume average between neighboring flux surfaces. The *thermal* coefficients $D_{3\mathrm{j}}^\mathrm{b}$ at each radial position are calculated by convolution of the monoenergetic bootstrap coefficient λ_bb with a Maxwellian:

$$D_{3\mathrm{j}}^\mathrm{b}=-\frac{3}{4\sqrt{\pi}\langle|\nabla\psi|\rangle^2}\int_0^\infty \mathrm{d}x\,e^{-x^2}x^{2(j+1)}\lambda_\mathrm{bb}\,,\quad \lambda_\mathrm{bb}=\frac{3}{2\rho_\mathrm{L}B_0\langle|\nabla\psi|\rangle}\langle\int_{-1}^{1}\mathrm{d}\lambda\,\hat{f}\lambda B\rangle\,, \tag{3}$$

where λ is the pitch parameter, $x = v/v_{\rm th}^{\rm b}$ is the particle velocity normalized by the thermal velocity of the electrons, $L_{\rm c}/l_{\rm c}^* = L_{\rm c}/(\tau_{\rm bb}v_{\rm th}^{\rm b})$ is the collisionality for thermal particles, $\tau_{\rm bb}$ is the collision time, B is the magnetic field module and $\rho_{\rm L}$ is the Larmor radius in the reference magnetic field B_0. At every radial position, these monoenergetic coefficients are calculated in independent simulations, for fixed values of the collisionallity $L_{\rm c}/l_{\rm c} = L_{\rm c}/(\tau_{\rm bb}v)$ and the electric field parameter $\Omega = E_{\rm r}/(vB_{00})$. B_{00} is the (0,0) harmonic of the field in Boozer coordinates.

One must note that the local ansatz underlying this approach is only partially fulfilled at certain positions of TJ-II [5]. This makes the diffusive picture of transport only approximately valid. Nevertheless, relaxation of the local ansatz would make the calculation of the bootstrap current profile impossible in terms of computing time. Also the monoenergetic picture breaks down for very large electric fields. Non-conservation of momentum below by the collision operator will be addressed in an incoming work.

Despite the facts stated in the first paragraph, the bootstrap current profile is not known with precision at TJ-II. The accurate calculation of the solution of Eq. (1) is a numerical challenge, since the error estimates for computations in the long-mean-free-path (*lmfp*) regime of stellarators are very large. This happens especially for TJ-II [3], which is characterized by a very complex magnetic configuration. The reason is that the current consists of an asymmetry in the particle distribution function caused by a combination of particle trapping, both helically and toroidally, and plasma radial gradients. Although the trapped particles do not provide a large current (its velocity is of the order of $\varepsilon v_{\rm th}$, with ε the inverse aspect ratio), the passing particle population equilibrate with them via collisions (providing a term $1/\varepsilon$ times higher than that of the trapped particles). When calculating this by means of a Monte-Carlo code, one has to be able to estimate the non-compensation of the current carried by co-passing particles and that carried by counter-passing particles. The code NEO MC [4] has been developed in order to overcome this problem. It combines the standard δf method (see Ref. [4] and references therein) with an algorithm employing constant particle weights and re-discretizations of the test particle distribution. This algorithm directly addresses the problem of the large numerical noise generated by deeply trapped particles, whose contribution to the total current is very small.

Results

Within this work, the monoenergetic coefficients have been computed for a wide range of collisionalities ($L_{\rm c}/l_{\rm c} = L_{\rm c}/(\tau_{\rm bb}v)$ between 10^{-5} and 3) and Ω (between 0 and 10^{-2}). Computations have been done at several radial locations, ρ^2=0.15, 0.25, 0.35 and 0.55. The flux surface label is defined as $\rho = \sqrt{\psi/\psi_0}$, where ψ_0 is the magnetic flux across the last closed magnetic surface. A part of the results, at the radial position ($\rho = 0.5$) is shown in Fig. 1. According to neoclassical theory, the transport coefficients are independent of the radial electric field in the very low collisionality regime. One can see in Fig. 1 that for each curve (unless for very low electric fields) this so-called collisionless limit has been reached, which is important for the computation of the thermal coefficients.

These thermal coefficients have been computed at each radial position, for given values of the electric field parameter, according to Eq. 3. Fig. 2 shows the normalized thermal coefficients D^{e}_{31} and D^{e}_{32} for $\rho = 0.5$ and $\rho = 0.75$ as a function of the collisionality for $\Omega = 10^{-4}$ (the coefficients are not very sensitive to the electric field, but one can see that the larger electric field reduces the ripple-trapped particle population thus reducing the current). For collisionaties around 5×10^{-2} that correspond to electrons in NBI plasmas, one can see that D^{e}_{32} is quite larger than D^{e}_{31}. This happens at all the radial positions calculated. Therefore the main contribution to the bootstrap current will come from the temperature gradient.

Finally, the thermal coefficients and the plasma gradients are retrieved and the bootstrap current profile is calculated following Eq. (2). Fig. 3 shows plasma profiles characteristic of TJ-II plasmas heated with NBI under lithium coating. Given the flat temperature profiles, the density gradient term would be expected to dominate if D^{e}_{31} and D^{e}_{32}. The results are shown in Fig. 4, where only the electron component, which is expected to be much higher for a plasma in the ion root, is calculated. As expected, the main contribution comes from the electron temperature gradient. The smallness of the error bars is remarkable.

Conclusions

In this work, we show that NEO-MC is able to provide, for the first time, calculations of the contribution of the *lmfp* regime to the bootstrap current of TJ-II with high accuracy. We present computations of the monoenergetic bootstrap coefficient at several radial locations for a wide range of collisionalities and radial electric fields. This allows for a precise energy convolution and therefore an estimate of the profile of the bootstrap current.

Since the bootstrap current is expected to change, even qualitatively, for different magnetic configurations, more calculations are foreseen in order to explore the wide range of configurations of TJ-II. This calculation will allow to include more accurately finite-beta effects in the studies on the relation between confinement and magnetic configuration.

References

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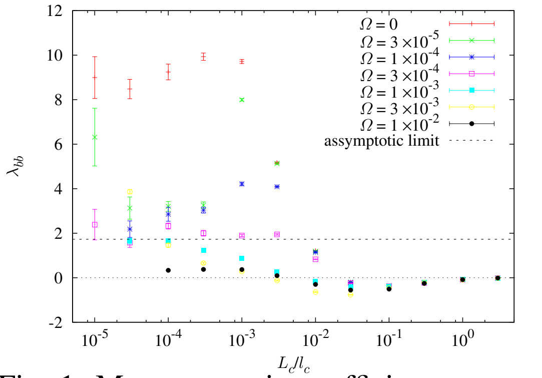

Fig. 1: Monoenergetic coefficients at $\rho = 0.5$.

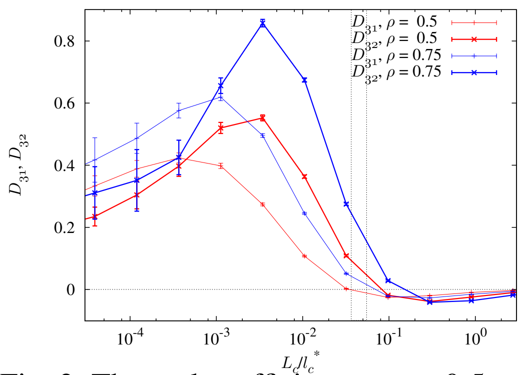

Fig. 2: Thermal coefficients at $\rho = 0.5$.

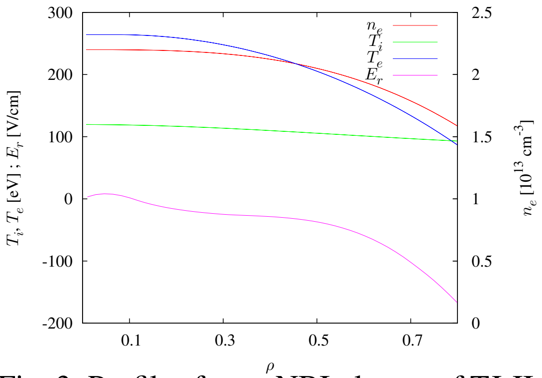

Fig. 3: Profiles for an NBI plasma of TJ-II.

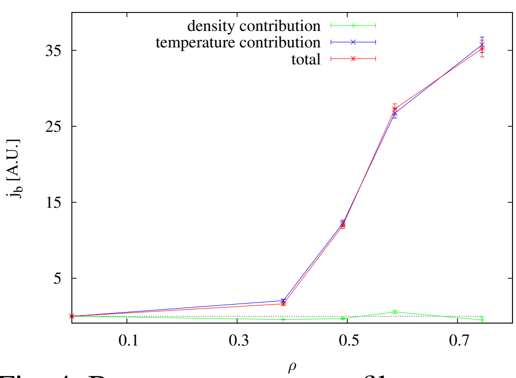

Fig. 4: Bootstrap current profile.

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