Electron Bernstein driven and Bootstrap current estimations in the TJ-II stellarator

F. Castejón (1,2), J.L. Velasco (1), J.M. García-Regaña (1), K. Allmaier (3), Á. Cappa (1) W. Kernbichler (3), N.B. Marushchenko (4), M. Tereshchenko (2) ,

(1) Laboratorio Nacional de Fusión, Asociación EURATOM-CIEMAT, Madrid, Spain
(2) BIFI: Instituto de Biocomputación y Física de Sistemas Complejos, Zaragoza, Spain
(3) Institut für Theoretische Physik - Computational Physics, Technische Universität Graz, Association EURATOM-ÖAW, Graz, Austria
(4) Max-Planck-Institut für Plasmaphysik, EURATOM-Association, Greifswald, Germany

email: francisco.castejon@ciemat.es

Abstract. The main toroidal current sources in stellarators are the bootstrap and the externally driven current by the heating systems. In this paper we present preliminary calculationts that will allow to calculate the bootstrap current and the one driven by electron Bernstein waves (EBCD) in the NBI plasma regime in the TJ-II stellarator. The calculation of the first one is very challenging in TJ-II since the DKES code, the usual neoclassical tool, gives large error bars in the calculation of the long mean free path regime. The electron Bernstein current drive can be very useful for modifying the rotational transform profile in these overdense plasmas and we show here several a linear method of calculation fast enough to be included in a ray tracing code. The addition of these current sources cannot be done straightforwardly since it could be possible that some synergetic effects appear.

1. Introduction

The control of the total parallel current may lead to the possibility of continuous operation in tokamak plasmas by driving non inductive currents and it can also provide access to improved confinement regimes in stellarators, by means of control of the rotational transform profile. In fact, one of the main lines of research at the stellarator TJ-II is the relation between confinement and the magnetic configuration, putting emphasis on the rotational transform profile [1]. The research on driving non-inductive currents both in tokamaks and stellarators is hence a key topic. The studies on current drive is even easier to perform in stellarators than in tokamaks due to the absence of Ohmic current that could mask other current sources.

The two main non-inductive parallel current sources in plasma confinement devices are the bootstrap and the ones driven by external means, like radio frequency or NBI. In this work we are concentrating on the theoretical study of bootstrap current and on the one driven by electron Bernstein waves (EBW) in TJ-II. The reason for paying attention to the current generated by such type of waves is that current drive (CD) systems must be appropriated to work on overdense plasmas, since this could be mandatory in a reactor. Therefore, electron Bernstein waves (EBW), which do not present density cut-off have been considered as a promising CD system for future magnetic confinement fusion devices. Moreover, the fact that the waves can reach large values of the parallel refractive index in the plasma makes that the resonant electrons have large parallel velocity hence being less collisional and having more contribution to the parallel current.

The EBW heating system [2] is in process of installation in TJ-II stellarator since previous theoretical heating studies have shown its feasibility [3]. In this work we present calculations of the bootstrap and the electron Bernstein waves (EBW) driven currents in the dense plasmas confined in a complex 3D confinement device like the TJ-II stellarator.

Despite of the importance of the bootstrap current, its value is not known with precision in TJ-II, since the usual tools to estimate it are not acurete in the lmfp due its extremely complex magnetic configuration. In fact, the neoclassical ordering and usual assumptions can fail in given TJ-II plasma characteristics [4], which provokes that usual numerical tools produce doubtful results. The bootstrap current, which is triggered by the radial gradients of the density and temperature, can be of the order of 1kA for TJ-II, which is a value high enough to have non-negligible effects on the rotational transform profile, thus changing the confinement properties of the device.

Bootstrap current and EBW driven current will be the two sources of parallel current in TJ-II NBI plasmas, characterised by their high density and collisionality. Although the bootstrap current is expected to be low in the NBI regime, the EBW driven current will be intense.

The reminder of this paper is organised as follows. Section 2 is devoted to the development of tools for the bootstrap calculation in TJ-II plasmas. Section 3 shows the EBCD calculations. Conclusions and discussion come in section 4.

2. The Bootstrap current calculations

As a first step in this work, we present computations for the radial profile of the bootstrap current for NBI plasmas of TJ-II. The precise calculation of the bootstrap current is a numerical challenge, since it arises from the non-compensation of the current carried by co-passing particles and that carried by counter-passing particles. As a consequence of this, the error estimates for computations of the bootstrap current, specially in the long-mean-free-path (lmfp) regime of stellarators, are very large. This issue is particularly relevant for the long mean free path regime of stellarators, particularly for TJ-II [5], which is characterized by its very complex magnetic configuration. In fact the results produced by DKES (Drift Kinetic Equation Solver) [6], the usual code to estimate the non-diagonal terms of transport matrix are doubtful for TJ-II, since the error bars of the bootstrap coefficient are very large. ISDEP, a global Monte Carlo code was developed to

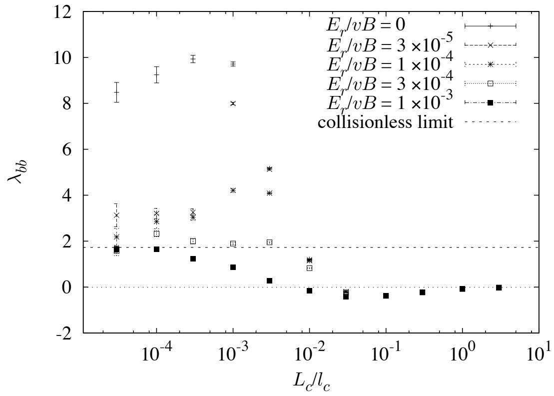

***Figure 1**. Monoenergetic coefficients for the bootstrap current calculated with NEO-MC for TJ-II, as a function of the mean free path, normalised by the thermal bounce path for the radial position given by the flux ψ =0.25. The calculation is done for several electric fields.*

overcome the difficulties of the neoclassical calculations in TJ-II, but this code only runs for ions and no information is produced on the behaviour of electrons [7].

A new code, NEO-MC [8], has been developed in order to overcome the difficulties that appear in TJ-II for neoclassical calculations. It combines the standard delta-f method with an algorithm employing constant particle weights and re-discretizations of the test particle distribution. In this way, it achieves a much better scaling of the error estimates with the collisionallity. In order to estimate the bootstrap current, one has to simplify the Drift Kinetic Equation that describes the evolution of the particle distribution function. The current for every plasma species *b* can be written in terms of the thermal coefficients as:

$$j_{\parallel}^{b} = -en_b \langle |\nabla \psi| \rangle \left(D_{31}^{b} \left(\frac{d\ln(n_b)}{d\psi} - q_b \frac{E_r}{T_b \nabla \psi} \right) + D_{32}^{b} \frac{d\ln(T_b)}{d\psi} \right)$$

The thermal coefficients D_{31} and D_{32} are given in terms of the monoenergetic coefficient λ_{bb} by:

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

We calculate the transport coefficients D_{31} and D_{32} which relates the bootstrap current to the density gradient. One must note that the local ansatz underlying this approach is only partially fulfilled at certain positions of TJ-II, which makes the diffusive picture of transport only approximately valid [4]. Nevertheless, omitting of the local ansatz would make the calculation of the bootstrap current profile impossible in terms of computing time. Specifically, we have calculated the monoenergetic coefficient l_{bb} for a wide range of the collisionallities (L(c)/l(c) between 10^{-5} and 3) and electric field parameters (E(r)/vB between 0 and $3\mathrm{x}10^{-3}$), and we have repeated these calculations at several radial locations. Figure 1 shows such results at r=0.25: for a given (non-zero) value of the radial electric field, as the collisionallity lowers, the calculated value of the monoenergetic coefficient converges to the so-called collisionless limit. The next step in the calculation of the bootstrap coefficient is to convolute the results shown in the picture with a Maxwellian. In order to do this, it is mandatory to have reached the collisionless limit with enough accuracy. We have shown that NEO-MC is able to provide, for the first time, calculations of the contribution of the long mean free path (lmfp) regime to the bootstrap current of TJ-II with very low error estimates. The next step is to estimate the bootstrap current, for which it is mandatory to consider the actual plasma profiles.

3. The EBW driven current

EBW are foreseen as the perfect complement for plasma heating in the NBI regime in TJ-II. This is because it provides power to these overdense plasmas without increasing the density. In this way, EBW can contribute to avoid the radiative collapse and to produce plasmas with hotter electrons.

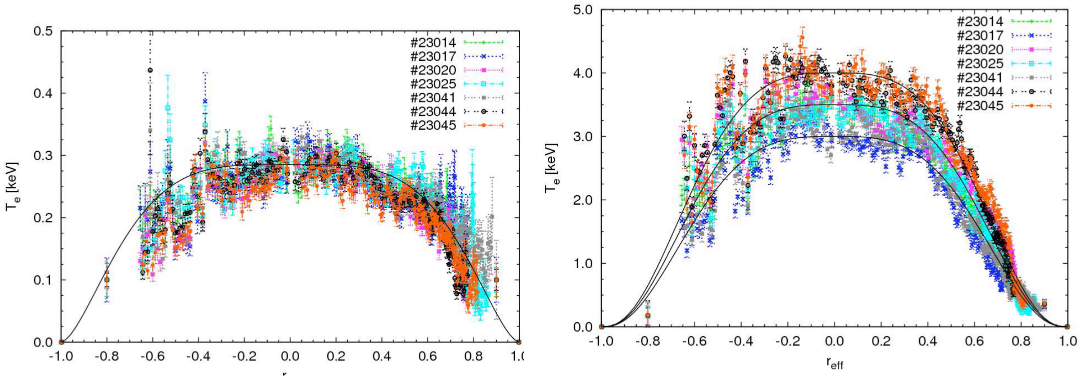

Figure 2*. Typical NBI plasma profiles in TJ-II. Left: density profile. Right: temperature profile.*

One of the contributions of the EBW heating is the driving of currents (EBCD). EBCD is estimated in these TJ-II plasmas using the linear theory by means of several methods [9] in order to use every approximation in the regime for which it is valid. The results show that EBCD is a valuable tool for tailoring the rotational transform profile in TJ-II NBI plasmas.

The Electron Cyclotron Current Drive (ECCD) in TJ-II was previously estimated and compared with the experimental results [10] with good agreement, which gives us confidence on the present estimation of the EBCD expected in EBW-NBI-heated plasmas in TJ-II. EBCD works in overdense plasmas like ECCD does in low density ones: by modifying asymmetrically the electron collisionality and the number of current carriers through diffusion into the trapping region [11]. These two mechanisms are the so-called Fisch-Boozer and Ohkawa mechanisms respectively. For a fast estimation of EBCD, different linear models based on the adjoint approach or Langevin equations techniques have been developed in order to simplify the task of solving the kinetic equation by avoiding the usage of time-consuming Fokker-Planck codes.

In this way it is possible to plug the CD calculations to the ray tracing code TRUBA for multiple ray simulations and even considering the evolution of the electron temperature and density profiles, which can have strong influence on the results [12], which implies launching multiple rays tens of times.

Among the available linear models for CD, recent development has been done in the direction of making these models preserve momentum conservation [13]. This is a requirement that the usual high speed limit models did not fulfil. For the present work, all models developed so far have been coupled to the ray tracing code TRUBA [14], in order to allow for its comparison.

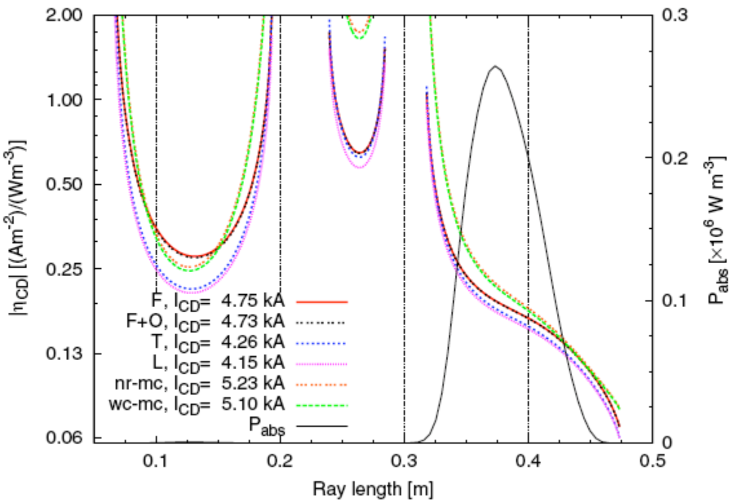

***Figure 3**. Values of the electron Bernstein current drive efficiency for several linear models, together with the absorbed power density profile. F is the Fisch model, F+O the Fisch model taking into account Ohkawa effect, i. e., particle trapping, T stands for Taguchi's model, L for the Lin-Liu model, while wr-mc and nr-mc denote weakly and non-relativistic momentum conservation models.*

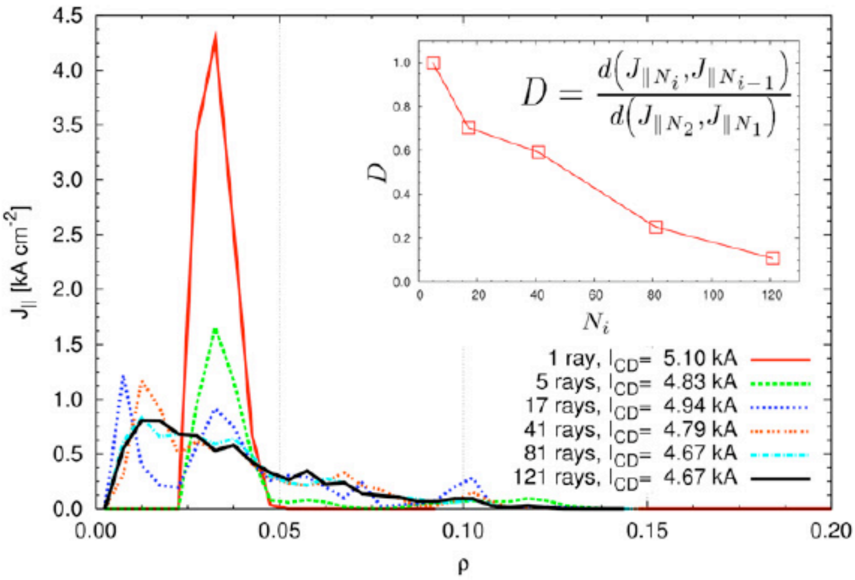

***Figure 4**. Electron Bernstein current driven profiles for several number of launched rays. It is seen that a number as high as 121 rays is enough to get reasonable level of convergency and gives an accurate enough value for the current.*

Figure 2 shows the plasma profiles for performing the calculations of this section, obtained by Thomson scattering disgnostic. Figure 3 shows the current drive efficiency estimated with the presently available models as a function of the ray paths. The important region to consider is just the one where absorbed power is non zero. The rays are traced in the complex 3D geometry with the plasma profiles of Figure 2. The models taken are marked with the following legends: F is the Fisch model, F+O the Fisch model taking into account Ohkawa effect, i. e., particle trapping, T stands for Taguchi's model, L for the Lin-Liu model, while wr-mc and nr-mc denote weakly and non-relativistic momentum conservation models. The references where all these models are presented can be found in [9], where the validity of these models for TJ-II is also discussed. According to the results of that work, the wr-mc model is the most suitable for EBCD estimates in TJ-II. Using this model, the current profile shown in Figure 4 is obtained, for different numbers of rays. The figure shows that a number of rays as high as 121 gives a reasonable accurate value for the current.

Finally, figure 5 shows the integrated current as a function of the density and temperature in TJ-II. These values are much larger than the ones of ECCD and high enough to modify the current density profile and, hence, to tailor the rotational transform profile in TJ-II. A monotonic behaviour with respect to the density is observed due to the decreasing dependence of the driven current with the collisionality and, hence, with the density, while a non-monotonic behaviour with respect to the temperature is observed. This effect is due to the combined effect of collisionality, which makes that driven current rises with temperature, and absorption that rises with temperature and changes the power deposition profile, locating it at radial zones where the driven current is not so high.

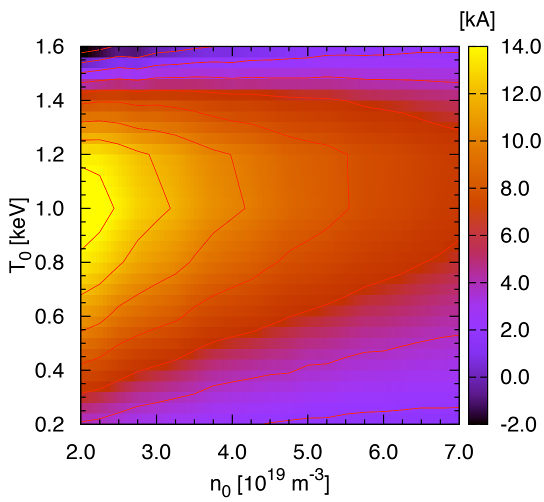

***Figure 5**. Total driven current by Bernstein waves in the TJ-II stellarator as a function of density and temperature. All the values are obtained by tracing 121 rays for plasma profiles like those shown in figure 2. The values of density and temperature correspond to the maximum values of the profiles.*

4. Conclusions and discussion.

The expected toroidal current sources in NBI TJ-II plasmas are discussed in this work. Tools to estimate the bootstrap current are adapted to the TJ-II geometry for the first time in order that an accurate value of the current can be estimated. The code NEO-MC is adapted to this complex geometry, which allows us to calculate the bootstrap current for all the possible regimes that appear in T-II plasmas, including the lmfp, thus overcoming the problems of accuracy we had with the standard tools.

On the other hand, driving currents by external means in these high density plasmas can be achieved by using electron Bernstein waves. It is well known that these waves can propagate in overdense plasmas being strongly absorbed close to the electron cyclotron resonances. These waves happen to present high values of the parallel refractive index, which makes them resonate with energetic electrons. Those electrons have large values of the parallel velocity and suffer low collisionalities, which make that the expected driven current are quite high. The driven current is estimated here by using a linear model based on the weakly relativistic calculations with applied momentum conservation techniques. The values obtained are larger than those expected by conventional electromagnetic waves [15].

Nevertheless the values of the two current sources obtained in the former calculations are not added in this work. One has to consider the combined effect of both effects in order to discriminate if the problem can be considered as linear or not. On the one hand, one has to take into account that electron Bernstein waves tend to push electrons in the perpendicular momentum direction in velocity space, which in principle could increase the fraction of trapped particles thus modifying the bootstrap current. On the other hand, the EBW will provoke an increase of the perpendicular particle flux, commonly known of pump-out [16], suffered especially by resonant electrons. This effect could tend to modify both the absorbed power and the driven current.

The way to ensure that the former effects are small and have low influence on both on EBCD and on bootstrap current is to check that the absorbed power density is small in the zones of maximum current.

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