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"Advanced"-δf Monte Carlo Simulation of NBI current drive in W7-X

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Introduction

In the planned stellerator experiment Wendelstein 7-X (W7-X) one is looking for mainly net-current-free discharges, where the bootstrap current is compensated by the neutral beam current drive (NBCD) or the electron cyclotron current drive (ECCD), because of the lack of an ohmic transformer. This is relevant since significant net current modifies the magnetic topology at the edge and thereby affects the operation of the island divertor.

This contribution provides a detailed analysis of different scenarios of neutral beam injection in W7-X. Especially the influence of co- and counter-injection on the absorbed power densities for electrons and ions as well as the ion slowing-down current density will be investigated using the "advanced"-δf Monte Carlo method [1].

The results for the neutral beam current are compared with the appropriate result for the bootstrap current obtained from predictive transport modeling[2] in order to see if the NBCD compensates the bootstrap current and if feedback control is possible.

Modeling

The neutral beam injection is modeled with Monte-Carlo techniques, the W7-code and the **A**dvanced **MO**nte-**C**arlo (AMOC)code [1]. The W7-code simulates the generation of neutrals in the NBI box up to the ionization within the plasma, and the AMOC-code the slowing-down of the fast ion population with the "advanced"-δf method. The "advanced"-δf approach starts with the ansatz for the distribution function $f = f_{\mathrm{M}} + f_1 + \delta f$, where f_{M} represents the Maxwellian. The second part, f_1, describes the flux-surface averaged part of the deviation from f. These two parts, f_{M} and f_1, are used in the marker equation with the appropriate sources and sinks. In the quasi-isodynamic W7-X configurations, fast particles remain near their "birth" flux surface for a long time. With the assumption of slowing-down on the flux surfaces, a simple Fokker-Planck solver delivers a rather good estimate for f_1 which is both very fast and accurate. A δf-scheme formulated in this way solves the problem in 2nd order to determine a δf which contains the desired information on drift effects. The fast ions are followed up to thermalization or until their escape from the plasma. For calculating the electron Okhawa current contribution, the adjoint approach both in the collisional [3] and in the collisionless [4] limit in the linear Fokker-Planck solver is used. In the predictive transport code for W7-X [2], the bootstrap current density is calculated by means of the DKES database of mono-energetic neoclassical coefficients for the specific configuration (with energy convolution for evaluating the thermal neoclassical transport matrix). The radial electric field, E_r, is calculated from the ambipolarity condition and used for the determination of the boostrap current and in the Monte-Carlo simulation. From the current balance the influence on the ι-profile is estimated.

The “advanced” δf method

The “advanced” δf method is an extension of the δf approach which additionally to f_{M} takes the non-equilibrium part f_1 out of the distribution function and concentrates the simulation on the remaining part $\delta f = f - (f_{\mathrm{M}} + f_1)$.

Consider the drift kinetic equation, where the distribution function $f(\vec{x}, p = v_\| / v, v)$

$$V(f) - C^p(f) - C^v(f) = S_{NBI} - S_l \tag{1}$$

and

$$V = (\frac{vp}{B}\mathbf{B} + \mathbf{v}_{\nabla B} + \mathbf{v}_{E\times B}) \cdot \nabla + \dot{p}\frac{\partial}{\partial p} + \dot{v}\frac{\partial}{\partial v} \tag{2}$$

represents the Vlasov operator where $vp\mathbf{B}/B$, $\mathbf{v}_{E\times B}$ and $\mathbf{v}_{\nabla B}$ are the drift velocities of the guiding center and the terms $\dot{p}$, $\dot{v}$ are

$$\dot{p} = -\frac{1-p^2}{2B^2}\left(v\mathbf{B}\cdot\nabla B + \frac{p}{B}(\mathbf{B}\times\nabla B)\cdot\nabla\Phi\right), \dot{v} = -v\frac{1+p^2}{2B^3}(\mathbf{B}\times\nabla B)\cdot\nabla\Phi.$$

$C^p(f)$ represents a pitch angle and $C^v(f)$ an energy collision operator. The term S_{NBI} describes a particle source due to the NBI and S_l describes the particle losses. f_1 is obtained as the solution of the equation

$$-C^p(f_1) - C^v(f_1) = \langle S_{NBI}\rangle - \langle S_l\rangle, \tag{3}$$

where $\langle ...\rangle$ is the flux-surface-averaging operator and the term S_l is used, e.g. $\dot{n}$ and $\dot{T}$ modeling, for the particle and power balance to obtain a stationary solution. Ignoring the Maxwellian f_{M} for the high energies leads to an inhomogeneous equation for δf

$$V(\delta f) - C^p(\delta f) - C^v(\delta f) = -v_{\nabla B}\big|_r\frac{\partial f_1}{\partial r} - \dot{p}\frac{\partial f_1}{\partial p} - \dot{v}\frac{\partial f_1}{\partial v}, \tag{4}$$

where $S_{NBI} - \langle S_{NBI}\rangle$ contains the information of co-and counter-drive and $S_l - \langle S_l\rangle$ is neglected. The right hand side leads to the marker equation

$$w = -\int\left(v_{\nabla B}\big|_r\frac{\partial f_1}{\partial r} + \dot{p}\frac{\partial f_1}{\partial p} + \dot{v}\frac{\partial f_1}{\partial v}\right)dt.$$

In order to get the part δf one assumes that the distribution function is highly localized, so that one can represent δf as the sum of delta functions in the form

$$\delta f = \sum_i w_i\delta(\vec{x} - \vec{x}_i)\delta(p - p_i)\frac{1}{v^2}\delta(v - v_i)$$

and the appropriate convolution yields the desired quantities.

Simulation setup

For the planning of the start-up phase of W7-X, NBI discharges are investigated which are expected to be typical. A H^0 in H^+ injection with four beam sources of 1.8 MW each with a mean pitch angle of $\pm 65^\circ$ and injection energy of 55 kV was chosen. The density and temperature profiles are shown in figure 1 and the power deposition profiles of fast particles are shown in figure 2; the average magnetic field was 2.5 T and the Z_{eff} was about 2.

In the first step, the radial electric field, E_r, is calculated from the ambipolarity condition. Then the distribution function f_1 and its derivatives are calculated by the Fokker-Planck solver and the Okhawa current is obtained. To initialize the simulation particles, their toroidal angle ϕ and the poloidal angle θ are distributed randomly. The radial position r, the velocity co-ordinates p, v and the weight w of each particle are chosen with a random shooting process according to the distribution function f_1. v is in every case chosen suprathermal. The simulation then starts by advancing the particle by an appropriate time step. After each integration step the collision operators are called. If a particle gets lost or thermalized it is replaced by a new one and the number of particles is kept constant.

The simulation runs until the total weight of all particles converges. During the simulation the time average over the weights of the particles at their radial positions is calculated in order to get the radial profile of the distribution function δf. For every call of the energy collision operator the separate power transfer from simulation particles to background ions and electrons is stored to derive the power deposition profiles. The ion-slowing down current can then be directly determined as a moment of the distribution function.

Finally, the current balance of the bootstrap current and the NBCD is made and the influence on the $\iota\!\!\!-$-profile is estimated.

Simulation results

As a first result, the densities of NBCD for co- and counter injection and the bootstrap current are shown in figure 3. The amount of bootstrap current carried by electrons is 33.3 kA and by ions is 3.4 kA, the total NBI driven current in co-direction is 24.2 kA and in counter-direction 26.3 kA. The similar behavior of co- and counter injection is due to the strong optimization on drift orbits of fast particles in W7-X. The results for NBI driven currents clearly exceed the bootstrap currents of electrons and ions in the central region. This means that it is possible to compensate the bootstrap current with the NBCD. In such scenarios, a net-current-free discharge is reached after 28.9 s in both cases.

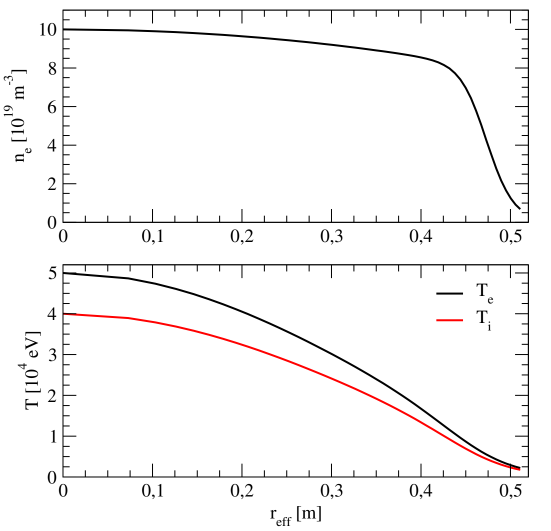

Figure 1: Electron and ion densities and temperatures as assumed for a typical discharge in W7-X.

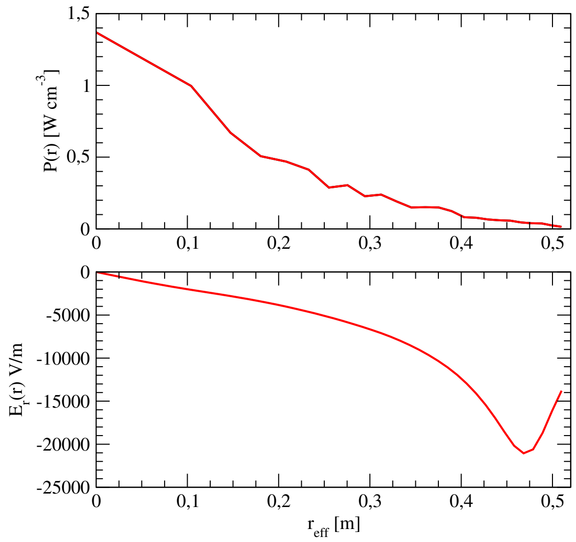

Figure 2: Power density ("birth") profile of fast particles and radial electric field. The injection energy is 55 kV and 14.4 MW.

The resulting ι-profile compared with the ι-profile of the equilibrium is plotted in figure 4. In the co-injection case the ι-profile the equilibrium ι exceeds in the central region and in the counter-injection the ι-profile is lower compared to equilibrium ι. This makes it difficult to use the NBCD for feedback control.

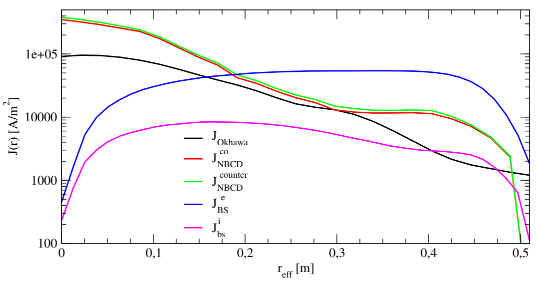

Figure 3: Densities of co-(red), counter-(green) NBI, Okhawa(blue) and bootstrap current.

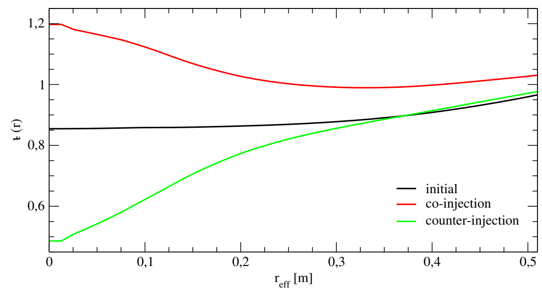

Figure 5: ι-profiles of the initial equilibrium and the influence of the current drive.

References

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