ELSEVIER

Journal of Nuclear Materials 290–293 (2001) 953–956

journal of nuclear materials

www.elsevier.nl/locate/jnucmat

Helium compression analysis for ASDEX Upgrade with fluid and kinetic codes

D. Reiser [a,*], R. Schneider [b], D. Coster [b], W. Ullrich [b], H.S. Bosch [b]

[a] *Institut für Plasmaphysik, Forschungszentrum Jülich GmbH-IPP-T, EURATOM Association, Trilateral Euregio Cluster, Leo Brandt Strasse, D-52425 Jülich, Germany*

[b] *Max-Planck-Institut für Plasmaphysik, EURATOM Association, Boltzmannstr. 2, D-85748 Garching, Germany*

Abstract

In this numerically oriented paper we present first results of a self-consistent coupling of the linear impurity Monte-Carlo code DORIS with the code package B2-EIRENE. First we consider conditions under which the impurities of interest are of such a small concentration, that the trace impurity assumption is justified. Thus the numerical procedure in such cases includes only a coupled DORIS-EIRENE run on a fixed plasma background. As an example we present results of a numerical analysis of He-compression experiments performed on ASDEX Upgrade. Results obtained with the coupled DORIS-EIRENE procedure are compared with those provided by self-consistent calculations of the B2-EIRENE package in which the impurities are treated as a fluid.

Keywords: Transport; Modelling

1. Introduction

Low ionized impurity ions can exhibit – under certain conditions like steep temperature gradients or non-thermalized sources [1,2] – different characteristics than assumed in fluid models, where the distribution in velocity space is required to be near maxwellian. This is often supplemented by the even stronger assumption of complete thermalization with respect to the background plasma temperature. This makes it desirable to describe those particles by an appropriate kinetic model consistent with the often well-justified fluid modelling of the main plasma (hydrogen and electrons) and the higher charged impurity ions. In this work we report on a combination of a drift kinetic simulation of the impurities, i.e., the DORIS code [1], with fluid modelling of the main plasma, the B2 code [3], and a kinetic algorithm for the neutrals (hydrogen and impurities), the EIRENE code [4]. This approach will be evaluated by a comparison with results of the B2-EIRENE code package [5], which treats all the impurities in the fluid limit. The concept of the code coupling is sketched in Fig. 1. The non-linearity of the simulation is handled by an iterative procedure. In one iteration cycle the codes are run one after another (in the order B2 → EIRENE → DORIS → B2 etc.), each for a certain time interval dependent on the characteristic time scales of the transport and atomic processes taken into account. After each run the results are distributed to the other codes and serve as an input for the next cycle.

2. Model equations

In the numerical model of the DORIS code the following set of coupled drift kinetic equations is implemented:

$$\frac{\partial \bar{f}_Z}{\partial t} = -\frac{\partial}{\partial x_\parallel}\left(v_\parallel \bar{f}_Z\right) - \frac{\partial}{\partial v_\parallel}\left(\frac{Ze}{m} E_\parallel \bar{f}_Z\right) + \sum_a \frac{\partial}{\partial v_a}\left(K_a \bar{f}_Z\right) + \frac{1}{2}\sum_{a,b}\frac{\partial^2}{\partial v_a v_b}\left(D_{ab}\bar{f}_Z\right) + \frac{\partial^2}{\partial x_\perp^2}\left(D_\perp \bar{f}_Z\right) + S_Z^+ - S_Z^-. \quad (1)$$

* Corresponding author. Tel.: +49-02461 61 5075; fax: +49-02461 61 2970.

E-mail address: d.reiser@fz-juelich.de (D. Reiser).

0022-3115/01/$ - see front matter
PII: S0022-3115(00)00657-7

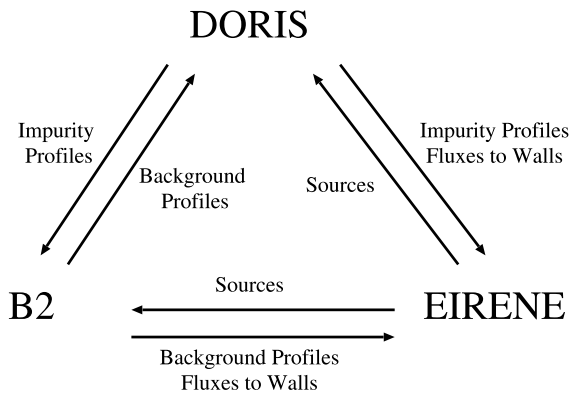

Fig. 1. Schematical sketch of the comunication between the codes used in the calculations.

This governs the evolution of the transformed distribution functions $\bar{f}_Z(\mathbf{x}, v_\parallel, v_\perp, t) = v_\perp f_Z(\boldsymbol{x}, v_\parallel, v_\perp, t)$ of different charge states Z in time and in the 3D–2D phase space (3D in real and 2D in velocity space). $x_\parallel$ and $x_\perp$ refer to directions parallel to the magnetic field lines and radially outwards across the flux surfaces, respectively. $v_\parallel$ is the component of the single particle velocity along the field lines and $v_\perp$ denotes an average velocity perpendicular to them. The first two terms on the RHS of the Fokker–Planck equation (1) describe the motion along the magnetic field line. m is the mass of the impurities, e the elementary charge and $E_\parallel$ is the stationary electric field, determined by the use of the electron momentum equation

$$E_\parallel = -\frac{1}{e}\left(1.71\frac{\partial T_e}{\partial x_\parallel} + \frac{T_e}{n_e}\frac{\partial n}{\partial x_\parallel}\right). \tag{2}$$

The third and fourth terms constitute the drift kinetic Coulomb collision term, where each of the indices a and b run over both $\parallel$ and $\perp$. The drift and diffusion coefficients K_a and D_{ab} describe the interaction of the impurities with a slightly distorted maxwellian background. The detailed formulas for these coefficients are elucidated in [1]. The fifth term describes an anomalous diffusive radial transport in real space. In the calculations the diffusion coefficient $D_\perp$ is set to a constant value of 1 m^2/s. The remaining terms S_Z^+ and S_Z^- in (Eq. 1) describe sources and sinks due to ionization, recombination, recycling at the walls, etc. In the numerical algorithm a large number of particle trajectories are constructed according to discrete equations of motion for each time step Δt. The calculations are performed for a given background plasma, which parameters determine the Coulomb collision term and are provided by the B2 code. The sources and sinks due to recycling at the walls and ionization of neutral impurities are calculated by the EIRENE code using the same main plasma parameters of the B2 run. Drift effects are neglected in the calculations, so equation (1) is equivalent to the impurity transport model in the standard B2 code [3] for the trace impurity limit in which self-interaction is neglected. It has to be empasized that, in contrast to the B2 model, the kinetic model (1) provides automatically a temperature (mean energy) for each impurity species which does not have to be equal to the background temperature.

3. Boundary conditions for the impurities

In fluid modelling, the particular physical situation is defined by imposing boundary conditions. In most applications this is done by fixing the value of a physical quantity or its flux through the boundary. At the divertor plates one normally uses the so-called sheath conditions (Bohm criterion and heat fluxes modified by an appropriate sheath transmission factor [6]). For the transport to the walls usually the fluxes are set by the choice of an experimentally observed decay length and for the core boundary (interface to the core plasma) an appropriate density and heat flux are prescribed. In the linear kinetic Monte-Carlo modelling the transport of a single particle is determined rather by whether a grid boundary is absorbing, transparent or reflecting. In our kinetic calculations for the impurity ions we consider all outer boundaries and the divertor plates as completely absorbing. For the core boundary we adopt a simple reflection model which corresponds to a zero effective flux of impurities to the core. Possible recycling at the divertor plates or walls is taken into account in the EIRENE computations (based on impurity fluxes provided by the DORIS results) and is included in the total sources for the impurities in the next iteration step. It is clear, that the major difference of the kinetic and the fluid approach is that the kinetic Monte-Carlo algorithm does not need a prescription of the transport characteristics at the plates. The fluxes of impurity ions are not governed by a sheath model, but are merely the outcome of the transport simulation in the volume. This is justified, if the presheath electric field is essentially determined by the main plasma components.

4. Results for He-compression in ASDEX upgrade

Figs. 2–5 show the contour plots for He^{2+} density and poloidal flow profiles in the divertor chamber of ASDEX Upgrade for a high recycling scenario (high density of main ions close to the divertor plates).

The results were obtained on the one hand with DORIS-EIRENE calculations on a fixed background plasma prepared in advance by a B2-EIRENE calculation taking into account hydrogen ions and electrons and carbon as impurity. On the other hand we calcu-

Fig. 2. Density profile of He^{2+} calculated with DORIS (in m^{-3}).

Fig. 3. Density profile of He^{2+} calculated with B2 (in m^{-3}).

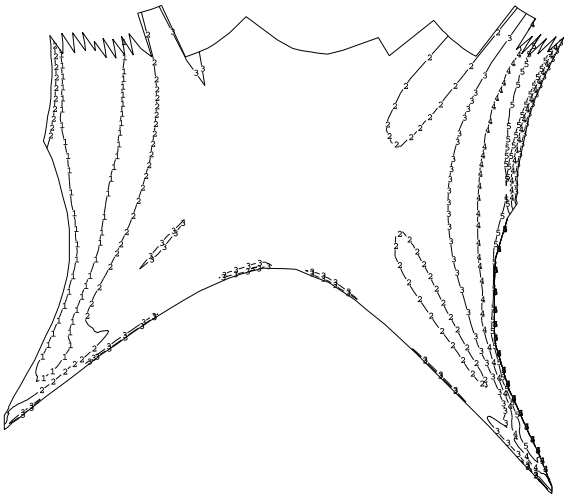

Fig. 4. Profile of the poloidal flow of He^{2+} calculated with DORIS (in m/s).

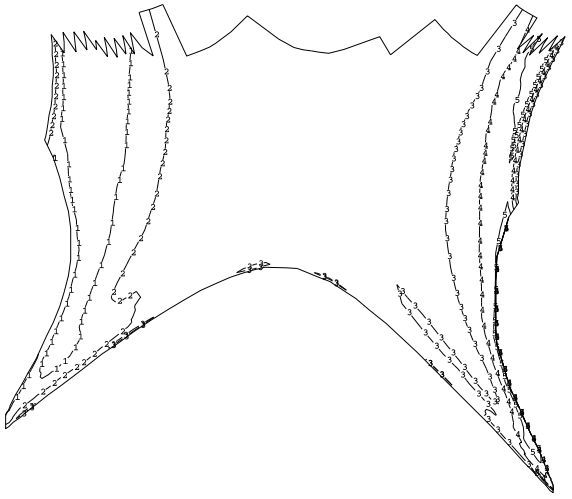

Fig. 5. Profile of the poloidal flow of He^{2+} calculated with B2 (in m/s).

lated the Helium profiles by the use of B2-EIRENE additionally taking into account the Helium impurities self-consistently. In the B2 computations a common velocity at the divertor plates of $\sqrt{p/\rho}$ is assumed, where p is the total pressure and ρ is the total mass density. Details concerning the other boundary conditions can be found in [6].

The density patterns of both He^{1+} and He^{2+} obtained with the different approaches show a remarkably good agreement qualitatively and quantitatively as well (although the absolute values can differ significantly in certain sll regions, because of a slight shift of the patterns due to the different handling of the geometry by the two codes). In all cases the poloidal velocity at the plates is the same as for the background plasma, indicating a dominant role of the friction forces. The results can be explained by the following characteristics of the

scenarios studied: (1) The impurities are maxwellized and/or the thermal forces do not play a dominant role compared with friction forces, (2) The boundary conditions used for the fluid calculations are matched well with the strong friction forces near the plates, (3) The self-interaction of the He-ions is negligible (because of its dependence $\sim Z^2 n_{\mathrm{He}}$ it is about a factor of 10^3 smaller than the interaction with the background plasma). All of these peculiar features are present in the specific application for the ASDEX Upgrade presented here. In particular the maxwellian character of the impurity distribution can be proved by the calculation of velocity-averaged thermal forces leading to known analytical results [7].

So the results presented can be interpreted as a nice example of the two codes confirming each other near the fluid limit. It can also be concluded, that the kinetic approach meets the requirement, reproducing the fluid results for cases in which the kinetic effects are expected to be of minor importance. Further studies for scenarios with low densities of electrons, i.e., low recycling of hydrogen, in the divertor chamber demonstrate, that the overall agreement is less conclusive. Although the density patterns of helium agree fairly well, the calculated poloidal velocities (fluxes) in the kinetic approach differ by a factor of 2 compared to the fluid approach, i.e., they are smaller for He^{1+} and larger for He^{2+}. This can be explained by the strong effects due to thermal forces and the parallel electric field caused by steep gradients in the vicinity of the divertor plates. In those computations the common velocity for all ion species is an inappropriate boundary condition in the fluid modelling, which neglects the competition of the thermal and electric forces. Practically, the results presented are a good example for a postprocessing analysis of impurity transport using results for the main plasma obtained in foregoing calculations. Such calculations can be done on a Cray-T3E computer, using 64 PEs, in about 90 min (corresponding to 5×10^5 simulation particles for good statistics). A self-consistent fluid calculation would require several hours or days on a usual RISC 6000 machine to obtain the same results.

References

[1] D. Reiser, D. Reiter, M.Z. Tokar', Nucl. Fus. 38 (1998) 165.
[2] J.D. Hey et al., Contrib. Plasma Phys. 34 (6) (1994) 725.
[3] B.J. Braams, Net-Report EUR-FU IXII-80-87-68, Commun. European Communities, 1987.
[4] D. Reiter, Berichte des Forschungszentrums Jülich, Jül-2599 (1992).
[5] D. Reiter, J. Nucl. Mater. 196–198 (1992) 80.
[6] M. Baelmans, KFA-Jülich Report, Jül-2891 (1994).
[7] J. Neuhauser, W. Schneider, R. Wunderlich, K. Lackner, Nucl. Fus. 24 (1) (1984) 39.