A hybrid fluid–kinetic approach for 3D plasma edge transport in He-plasma at Wendelstein 7-X

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Introduction

The complex three-dimensional structure of the optimised stellarator Wendelstein 7-X can only partially be accessed by means of experimental measurements, as a consequence of the only quite limited number of measurements at distinct locations with different plasma cross-sections and properties. This highlights the importance of precise modelling (i.e. numerical bookkeeping) as an extended method for understanding the three-dimensional nature.

A plasma edge simulation code for treating complex magnetic configurations is the fluid plasma edge Monte-Carlo code in three dimensions (EMC3) [1] coupled to the kinetic (neutral) transport code EIRENE [2, 3]. EMC3 bases on a Monte-Carlo algorithm [4, Ch. 4.1] for a reduced set of Braginskii equations [5] formulated in a Fokker-Planck scheme while EIRENE solves extended Boltzmann equations. A detailed ab initio derivation of the EMC3 model equations can be found in [6, Ch. 2]. EMC3-EIRENE has been continuously improved and verified, but one remaining restriction was that the bulk ion species is limited to hydrogen isotopes, with higher-Z ions being treated as trace-impurities.

However, in initial operation phases Wendelstein 7-X (and probably also ITER) will be operated with helium plasma. For a more direct interpretation of first measurements, computational quantification of helium plasma flows in the edge is required. Therefore, an approach is presented and initiated for the simulation of helium plasma by slightly extending EMC3 to facilitate a treatment of the main plasma species with $Z \neq 1$ and expanding the use of EIRENE features within EMC3, e.g. its existing non-linear mode of operation, metastable resolved reactions and, most important, currently strongly reduced kinetic trace ion transport module.

Generalization of the EMC3 model equations for $Z \neq 1$

The simulation of He^{++} with EMC3 requires a generalization of the considered fluid equation to $Z \neq 1$. In the simply modified equations the particle balance reads

$$\nabla \cdot \left[n V_{i\|} \boldsymbol{b}_{\|} - D \boldsymbol{b}_{\perp} \boldsymbol{b}_{\perp} \cdot \nabla n \right] = S_{\text{ion}} , \tag{1}$$

with the plasma density $n = n_\mathrm{i} = n_\mathrm{e}/Z$, the parallel ion flow velocity $V_{\mathrm{i}\|}$, the normalized parallel and perpendicular magnetic field vectors $\boldsymbol{b}_\|$ and $\boldsymbol{b}_\perp$, and the ionization source S_ion due to electron impact collisions with neutrals. The momentum balance reads

$$\nabla \cdot \left[m_\mathrm{i} n V_{\mathrm{i}\|} V_{\mathrm{i}\|} \boldsymbol{b}_\| - \eta_\| \boldsymbol{b}_\| \boldsymbol{b}_\| \cdot \nabla V_{\mathrm{i}\|} - D \boldsymbol{b}_\perp \boldsymbol{b}_\perp \cdot \nabla \left(m_\mathrm{i} n V_{\mathrm{i}\|} \right) \right] = -\boldsymbol{b}_\| \cdot \nabla p + S_\mathrm{m} \;, \tag{2}$$

with the ion mass m_i, the parallel ion viscosity coefficient $\eta_\|$ (as defined in [5, Eq. 2.22]), the perpendicular diffusion coefficient D, the plasma pressure $p = n_\mathrm{e} T_\mathrm{e} + n_\mathrm{i} T_\mathrm{i}$, and the momentum source S_m due to charge-exchange and elastic collisions with neutrals. The electron and ion energy balances read

$$\begin{aligned} \nabla \cdot \left[\frac{5}{2} Z n T_\mathrm{e} V_{\mathrm{i}\|} \boldsymbol{b}_\| - \kappa_\mathrm{e} \boldsymbol{b}_\| \boldsymbol{b}_\| \cdot \nabla T_\mathrm{e} - \frac{5}{2} Z T_\mathrm{e} D \boldsymbol{b}_\perp \boldsymbol{b}_\perp \cdot \nabla n - Z \chi_\mathrm{e} n \boldsymbol{b}_\perp \boldsymbol{b}_\perp \cdot \nabla T_\mathrm{e} \right] \\ = k \left(T_\mathrm{i} - T_\mathrm{e} \right) + S_\mathrm{e,e} + S_\mathrm{imp} \;, \end{aligned} \tag{3}$$

$$\begin{aligned} \nabla \cdot \left[\frac{5}{2} n T_\mathrm{i} V_{\mathrm{i}\|} \boldsymbol{b}_\| - \kappa_\mathrm{i} \boldsymbol{b}_\| \boldsymbol{b}_\| \cdot \nabla T_\mathrm{i} - \frac{5}{2} T_\mathrm{i} D \boldsymbol{b}_\perp \boldsymbol{b}_\perp \cdot \nabla n - \chi_\mathrm{i} n \boldsymbol{b}_\perp \boldsymbol{b}_\perp \cdot \nabla T_\mathrm{i} \right] \\ = k \left(T_\mathrm{e} - T_\mathrm{i} \right) + S_\mathrm{e,i} \;, \end{aligned} \tag{4}$$

with the electron and ion temperature T_e and T_i, the parallel electron and ion thermal conductivity κ_e and κ_i (based on [5, Eq. 2.12 and 2.15]), the parallel electron and ion heat diffusivity χ_e and χ_i, $k = 3 m_\mathrm{e} n_\mathrm{e} / (m_\mathrm{i} \tau_\mathrm{ee})$ with τ_ee being the electron collision time (as defined in [5, Eq. 2.5e]), the energy source of electrons $S_\mathrm{e,e}$ and ions $S_\mathrm{e,i}$ due to plasma-neutral interaction (inclusive radiation), and the energy source S_imp due to impurity radiation.

The boundary conditions are adapted by generalizing the sound speed $c_\mathrm{s} = \sqrt{(Z T_\mathrm{e} + T_\mathrm{i})/m_\mathrm{i}}$.

Estimates for a typical helium ionisation and population distribution

The ion temperature of a typical plasma edge in a medium-sized fusion device ranges from a few eV to several 100 eV at densities in the order of $1 \times 10^{13}\,\mathrm{cm}^{-3}$. In a detached divertor, plasma densities in the order of $1 \times 10^{15}\,\mathrm{cm}^{-3}$ can be reached. A zero-dimensional estimate under non-local-thermodynamic-equilibrium conditions (using FLYCHK [8, 7]) provides first indications that a reasonable treatment of helium plasma as a single-fluid system with helium in the second ionisation state is justified. The graph in fig. 1 shows that inde-

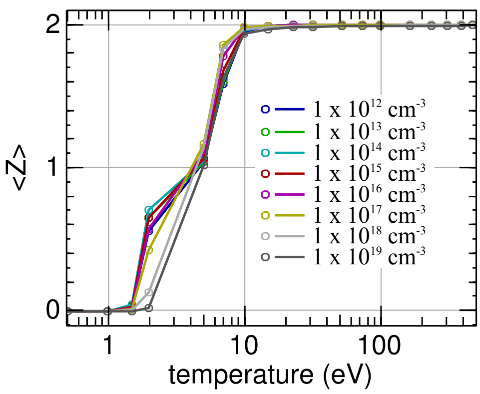

Figure 1: Helium averaged charge state for electron densities $1 \times 10^{12}\,\mathrm{cm}^{-3}$ to $1 \times 10^{19}\,\mathrm{cm}^{-3}$. Based on [7].

pendent of the density from a temperature of about 5 eV the dominant part of the helium ions is in the second charged state. At a temperature above 10 eV a fully ionized helium plasma is present.

A second estimate on the correct treatment of helium plasma can be made based on EIRENE test simulations by comparing the recycling flux from the targets with fluxes from volume-recombination. The simulations show that the dominant source for He^+ under the given conditions is ionisation from He rather than volume-recombination from He^{++}. Thus, it leads to the same conclusion as the zero-dimensional estimate under non-local-thermodynamic-equilibrium conditions: helium in the second ionisation state is dominant in the bulk of the plasma edge. Furthermore, this can be strengthened by comparing the simulated spatial distribution of He^{++}, neutral helium and He^+ near the location of the limiter in a typical limiter discharge at Wendelstein 7-X ($n_{i,up} = 1 \times 10^{13}\,cm^{-3}$, $P = 2\,MW$), see fig. 2. Only in the vicinity of the limiter the neutral helium density (dashed) is dominant in the scrape-off layer (SOL) but decreases rapidly in the plasma edge region, magnitudes below the He^{++} density (solid). A similar behaviour is seen for He^+ (dashed).

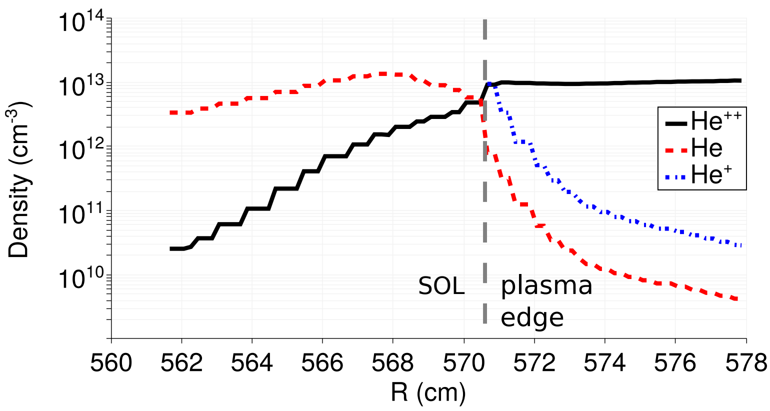

Figure 2: Comparison of density distributions of He^{++}, neutral helium, and He^+ calculated for typical Wendelstein 7-X limiter plasma with an upstream density of $n_{i,up} = 1 \times 10^{13}\,cm^{-3}$ and a heating power of $P = 2\,MW$. The radial profiles are taken along the mid-plane near the limiter.

Numerical treatment of He^+ and He^{++}

A treatment of He^+ with a fluid approach is not very appropriate because the short life time of He^+ ions prevents thermalisation and therefore a relaxation towards a Maxwellian distribution of the He^+ ions. An adequate treatment of He^+ is either quasi-static, when the characteristic transport lengths are much shorter than the length scale of interest, or even kinetic, otherwise. In the quasi-static approach the ion is stopping at its place of birth until it gets further ionised or recombines. The simplest approach for a kinetic treatment is the movement along the magnetic field lines which is already implemented in EIRENE. Additional effects like ion drifts are neglected.

The atomic and molecular collision data as originally presented by Janev *et. al* [9] and Fujimoto [10] (for helium) are extended and stored in the HYDHEL [11] and AMJUEL [12] database to treat the different atomic processes within EIRENE simulations (for further details on the treatment of helium reactions see [13]). The following atomic processes are considered:

$$e + \mathrm{He}(1|1\mathrm{S}) \rightarrow e + \mathrm{He}^{+} + e \qquad [12, \mathrm{rx\ H.4\ 2.3.9a}],$$

$$\mathrm{He}^{++} + \mathrm{He} \rightarrow \mathrm{He} + \mathrm{He}^{++} \qquad [11, \mathrm{rx\ H.1/H.3\ 6.3.1}],$$

$$e + \mathrm{He}^{+}(1\mathrm{s}) \rightarrow \mathrm{He}(1|1\mathrm{S}) + ... \qquad [12, \mathrm{rx\ H.4\ 2.3.13a}],$$

$$e + \mathrm{He}^{+} \rightarrow \mathrm{He}^{++} + e + e \qquad [12, \mathrm{rx\ H.4\ 2.2C}].$$

The dominant ion species He^{++} is treated with the fluid approach using the generalized model for EMC3 as presented above.

Summary and outlook

Using simple estimates it is shown that the dominant helium species in the plasma edge region is He^{++} which can be treated with a fluid approach, simulated by the extended model of the plasma fluid code EMC3. For a sufficient consideration of plasma wall interactions a treatment of neutral helium and He^{+} is also required which can be performed using the kinetic transport code EIRENE.

Future studies need to quantify the applicability of a quasi-static over a kinetic approach for He^{+} and the use of metastable resolved over unresolved transport. Processes currently neglected like $He^{++} \rightarrow H^{+}$ recombination [12, rx H.4 2.3.2C] and He–He^{+} charge-exchange [11, rx H.1/H.3 5.3.1] will be considered via the non-linear collision model of EIRENE.

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