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Recycling and density control in TJ-II plasmas based on 1-D transport calculations

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Introduction

A notable difficulty when studying particle transport is the knowledge of the sources, especially those associated with recycling processes. We use a model for kinetic equation (the one included in the ASTRA package [1]) to calculate the neutral particle distribution in TJ-II plasmas. More important than the kinetic model itself is the way we act on its boundary conditions: based on pressure measurements in the vacuum chamber of the TJ-II [2], we change the neutral density in the plasma boundary depending on transport outflows and puffing. The resulting electron sources allow us to analyse the sensibility of the plasma to cold gas puffing depending on the recycling conditions. The problem of density control actually found in the experiments is thus transferred to the numerical calculations.

In this work we study the ratio between recycling and gas-puffing flows towards the plasma in typical Electron Cyclotron Heated discharges of the TJ-II stellarator. For densities below ECH cutoff, density control via gas puffing is difficult because the range of stable densities in the presence of a limiting wall is small. In the plasmas heated by energetic neutral beam injection, the experimentally observed increments in plasma density respond to strong additional particle sources not accounted by the neutral beam itself (see Ref. [3]).

The main aim of this work is to provide a first stage of understanding before, in a next exercise, we adopt a more complete numerical routine to evaluate the particle source from gas-puff and recycling. A systematic comparison with a 3D neutral transport model is envisaged to benchmark the 1D results that are obtained with the present approach. The inclusion of recycling in transport models might be essential in theoretical studies of plasma non-linear dynamics [4].

Equation and boundary conditions

In this work we study the problem of density control based on the recycling conditions at the wall of the vacuum chamber. To make things simple we use a simplified one-dimensional evolution equation for the neutrals distribution function (see, e.g., Ref. [5]):

$$v\frac{\partial f_N}{\partial x} + n(\mathbf{r})(\alpha+\beta) f_N = n(\mathbf{r})\beta f_{Mi}\int f_N(\mathbf{v}')d^3\mathbf{v}', \qquad (1)$$

where α and β are appropriate integrals of the cross sections of different processes affecting the sources of neutrals. We simplify the neutrals distribution at the boundary:

$$\int f_N(\mathbf{v}')d^3\mathbf{v}' = n_N \left[\frac{\sqrt{3}}{2}\delta\left(v - \frac{v_i}{3}\right) + \frac{\sqrt{3}}{2}\delta\left(v + \frac{v_i}{3}\right) \right]. \tag{2}$$

Recycling is studied by acting on the boundary values

$$f_N(x = \pm a) = n_{\rm CL}\delta(v \pm v_{\rm CL}) + n_{\rm WM}\delta(v \pm v_{\rm WM}), \tag{3}$$

where we use energies instead of velocities and take the following values: $\mathscr{E}_{\rm CL} = 0.002$ keV, $\mathscr{E}_{\rm WM} =< T_i > /2$ keV. The densities $n_{\rm CL}$ and $n_{\rm WM}$ at the boundary plasma are modified during the calculation depending on transport and gas puffing rates.

In this simplified one-dimensional description of the source term we are not taking into account any of the intrincacies of the plasma-wall interaction in the TJ-II. We consider that there is a recycling factor R that relates the incoming particle flows $\Gamma_{\rm E}$ with the ion outflow, $\Gamma_{\rm E} = R\Gamma_i = R\Gamma_e/Z_{ef}$; and another factor that accounts for the vacuum chamber geometry, κ.

To modify the incoming fluxes we need a relationship between $\Gamma_{\rm E}$ and $n_{\rm WM}$. If the warm neutrals density is related to the ion outflow through the speed (or boundary velocity) of the warm neutrals, then κ accounts for the average velocity component perpendicular to the plasma boundary. Considering the effective charge of outflowing ions, we have

$$n_{\rm WM} = \frac{R}{\kappa Z_{ef} v_{\rm WM}}\Gamma_e.$$

Substituting $v_{\rm WM}$ by the corresponding thermal energy, we write

$$n_{\rm WM} = 2,28 \cdot 10^{-6} \frac{R}{\kappa Z_{ef} \mathscr{E}_{\rm WM}}\Gamma_e. \tag{4}$$

where the energy is given in keV and the electron perpendicular flow in units of 10^{19} m^{-2}s^{-1}. Finally, we set different values of $n_{\rm CL}$ to include the gas puffing.

Results

The main control parameters in the model are R/κ and the cold neutrals density (gas puffing). The uncertainty in the recycling is due to κ, which roughly summarizes the geometry of the recycling problem. It must be smaller than unity, but probably not less than 0.1. When we simulate ECRH plasmas of the TJ-II with a transport model that reproduces them reasonably, depending on κ we obtain a density $\sim 0,6 \times 10^{19}$ m^{-3} above which density control is difficult via gas puffing. In figure 1 we see the maximum line density (left vertical axis) that can be obtained via gas puffing in steady state. In the right vertical axis we label the net flows in each case for the gas puffed into the vacuum chamber necessary to obtain such maximum densities, and the corresponding recycling flows. The results are shown for two different values of Z_{ef}.

Large values of R/κ in Fig. 1 imply high recycling and a small maximum line averaged density. If one wishes to increase the density in those conditions, the plasma cooling (further penetration of neutrals), which changes more rapidly than the particle confinement time, set a positive feedback loop that can easily make the density grow uncontrollably. For ECRH plasmas this will make the plasma reach cut-off densities very rapidly. We see that (left part of Fig. 1) if the wall conditions allow for a smaller recycling, the density can be controlled reasonably well with the external gas puffing because the critical density gets high.

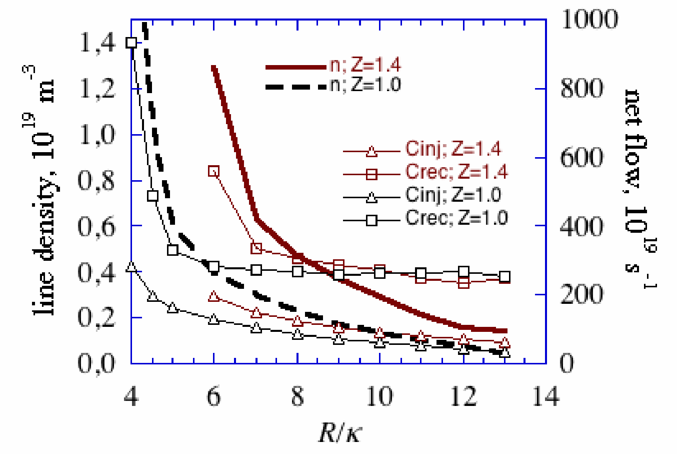

Figure 1: *Maximum line density (thick lines) that can be reached in a controlled way as a function of* R/κ*. Calculations are presented for* $Z_{ef} = 1.4$ *(brown) and* $Z_{ef} = 1.0$ *(black). The net flows due to gas puffing (triangles) and recycling (squares) that correspond to each density are shown in the right hand scale.*

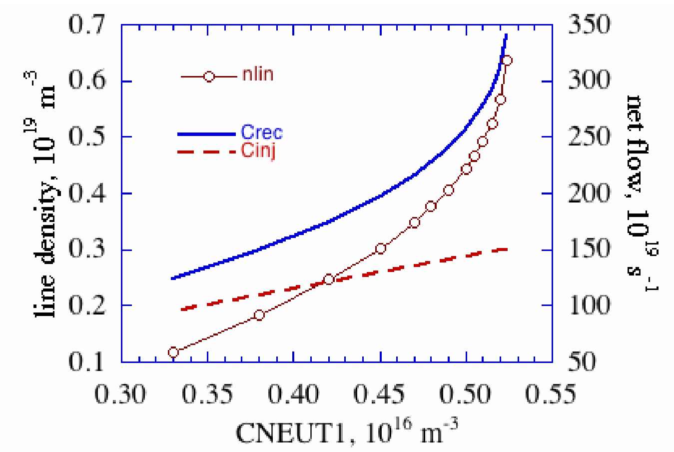

Figure 2: *Steady-state line densities obtained with* $R/\kappa = 7$ *and corresponding net flows* C_{CL} *and* C_{WM} *as a function of injected cold gas.*

An intermediate case (for example $R/\kappa = 7$ in Fig. 1) allows for increasing the density up to the values shown in Fig. 2. There we see the line densities (dashed line) that are obtained in a controlled way as the cold neutrals net flow towards the plasma is increased. The abscissa is labelled with the cold neutrals density in the plasma boundary, which is the gas puffing control knob.

When the recycling is low enough, the density can be controlled with the external gas puffing within the limits indicated by Fig. 1. A simulation of the

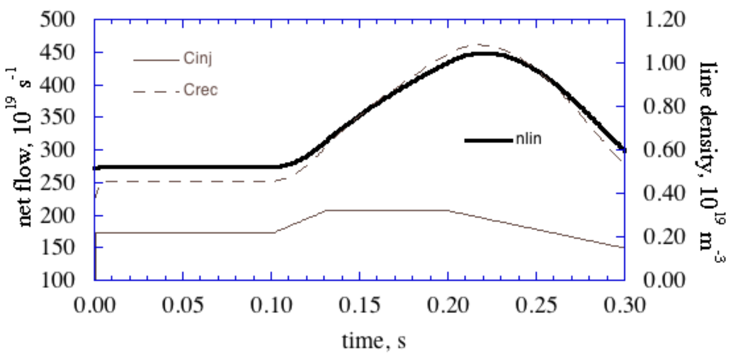

Figure 3: *Time evolution of the line density (thick line) in response to the gas puffing waveform. Shown are the net injected flow (thin continuous line) and the net recycling flow (broken line).*

response of the plasma is presented in Fig. 3, where we see how the line density (indicated with a thick line) obbeys the gas puffing waveform (thin line) although strongly modulated by the still dominant recycling inflow (dashed line), which is retarded due to the particle transport processes. In Fig. 3 we use $R/\kappa = 6$.

In summary, a simple model consisting of feeding back the plasma ion outflows via recycling, when coupled to a transport model that describes reasonably our ECRH plasmas, reproduces the problem of plasma density control. The same procedure can be used for NBI plasmas [3]. In a next step, we are going to include three-dimensional calculations that account reliably for the complexities of the plasma boundary and vacuum chamber of the TJ-II.

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