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Modelling of massive gas injection with SOLPS.

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Introduction. Plasma disruptions have three major negative effects on a tokamak: large mechanical forces, thermal loads and the generation of runaway electrons. Experiments on ASDEX Upgrade (AUG) and other tokamaks have shown that the magnitude of these effects can be significantly reduced by the massive injection of noble gas. The injected gas influences the evolution of the plasma disruption since it increases the plasma density and cools the plasma by dilution and radiation before the spontaneous thermal quench occurs. For all three types of load the crucial parameters are the magnitude and the speed of increase of the electron density in the plasma. Among the three types of load in ITER the suppression of the runaway avalanche poses the most severe requirement for the density increase. In this case, a density of the order of $5\ 10^{22}\ \mathrm{m}^{-3}$ is required. Since such a density increase is going to significantly affect the design of the pumping system, an effort must be made to understand which processes control the fuelling efficiency in order to maximize it.

In this work we use the code package SOLPS [1] to model gas injection in an AUG plasma and we compare the code results with the experimental measurements. The gas valve is treated as a point source and the neutral gas behaviour is modelled by the Monte Carlo module of the code, Eirene. The valve location, the quantity and the type of gas (D_2, He, Ne) are regarded as parameters and varied to assess their influence on the plasma density response. The code solves the transport fluid equations for the main plasma and impurity species along with a full description of the atomic and molecular processes in a 2D geometry. Gas ionization, density diffusion and plasma cooling are calculated accordingly. Large MHD activity and turbulence strongly modify the transport properties during impurity injection. We treat the heat and particle transport coefficients as parameters and vary them to test their influence on the fuelling efficiency. Experimental measurements of the density and thermal energy evolution are compared with the code prediction.

A parametric study. The first series of simulations is a parametric study aimed to understand the dependence of the fuelling efficiency, F_{eff} (defined as $\Delta\mathcal{N}_e/\mathcal{N}_{inj}$, i.e. the increase in the total number of electrons in the plasma divided by the number of injected atoms) on the properties of the injected gas. These simulations consist of injecting a constant flow of gas particles in the target plasma and in modelling the plasma evolution for Δt =3 ms (if not otherwise specified in Table 1). The gas parameters scanned are:

1) the gas flow, $d\mathcal{N}_{inj}/dt$, set equal to 10^{23}, 10^{24} and 10^{25} atoms/s;

2) the type of gas, chosen as deuterium (D_2), helium (He) and neon (Ne);

3) the distance of the valve from the plasma and the divergence of the gas flow. The valve is modelled as a point source (see Fig. 1) of mono energetic atoms. A maxwellian distribution of their velocity, which can play a role for valves far from the plasma, has not been implemented yet. In the case labeled "close" in Table 1 the valve is located at R = 2.25 m and the gas flow has an expansion angle $\alpha = \pi/4$; in the case "far" the valve is located at R = 2.50 m and $\alpha = \pi/2$. The plasma separatrix intersects the midplane at 2.15 m on the low field side.

The target plasma is obtained by feedback controlling the separatrix density at the outer midplane at about 1.5 10^{19} m^{-3} and heating a standard lower X-point AUG plasma with 5 MW. The resulting plasma has a thermal energy of 290 MJ and H-mode-type n_e and T_e profiles, as in the actual experiments. In this work we limit the simulation to the first 3 ms of the process of gas injection and we neglect the input ohmic power associated with the decay of the plasma current, which becomes significant at a later time.

The F_{eff} calculated after 3 ms of constant gas injection is summarized in Table 1. It is found that :

• F_{eff} decreases significantly with the increase of the rate of injected gas, $d\mathcal{N}_{inj}/dt$. The higher gas flow causes a larger cooling effect, a faster drop of the temperature and the recombination of multiple ionized ions. In the case of injection of 10^{25} atoms/s flow of He and Ne the thermal energy of the plasma has dropped of 92 and 86 % respectively; the corresponding average ionization charge of the impurities has dropped to 1.1 for both gases after 3 ms of gas injection. DIII-D experiments show that the F_{eff} of Ne decreases of a factor of 4 increasing $d\mathcal{N}_{inj/dt}$ from 0.3 to 3.6 10^{22} [2]; this agrees with our simulations. In the AUG experiments this dependence is not so clear. The F_{eff} also decreases during the simulation for all three gas species, more significantly at larger gas flows.

• The dependence of F_{eff} on $d\mathcal{N}_{inj}/dt$ is stronger at higher impurity atomic number. A comparison of the time evolution of the density and electron temperature profiles after 1 ms of gas injection (see Fig. 2) shows that He and Ne penetrate deeper than D_2 and cool the plasma more, Ne more than He. Experiments on AUG and DIII-D [2] indicate that F_{eff} is larger for He than for Ne, as predicted by our simulations.

• F_{eff} is always less than 50 % for D_2, because of the back scattering of one of the neutrals during the process of dissociation of the molecule.

• The F_{eff} is larger than 100% only at the low gas flows of $d\mathcal{N}_{inj}/dt = 10^{23}$ atoms/s for He and Ne . In this case the impurity atoms have a degree of ionization Z = 1.9 and 2.5 respectively at t = 3 ms.

• F_{eff} decreases significantly for Ne - less for D_2 and He - if the valve is moved away from the plasma and if the flow divergence increases. This is mainly a geometric effect. The transit time of the gas becomes a significant fraction of the simulation time when the valve is placed further away from plasma: Ne reaches the plasma after 0.8 ms when the valve is located at 2.5 m. In addition when the flow divergence is large (e.g. $\alpha = \pi/2$), the gas atoms, exiting the valve, reach the plasma spread over a time interval $\Delta t_\alpha = d(1 - cos\alpha)/c$. With a distance between valve and plasma d = 1.5 m, $\alpha = \pi/2$ and a sound speed $c = 400$ m/s then $\Delta t_\alpha = 0.7$ ms.

In AUG the valves located outside of the vessel (d = 1.5 m) exhibit a F_{eff} much smaller (factor of 2-3) than the in-vessel valve located close to the plasma [3]. The simulation suggests that a fraction of the atoms injected by the valve outside of the vessel does not even reach the plasma because their trajectories do not intersect the plasma. Another fraction of it reaches the plasma after the first atoms - the faster and perpendicularly directed - have caused the thermal quench.

Modelling a realistic shut down. A second series of simulations is aimed at modelling a specific discharge (shot 21758) in which a plasma (plasma current of 0.8 MA and thermal energy of 290 kJ) was shut down with 0.4 barl of neon within a few ms.

In this simulation the valve is located close to the plasma and it is assumed to open instantaneously. The gas flow is approximated by

$d\mathcal{N}_{inj}/dt = 6.9\,10^{24}$ atoms/s for t = 0-1 ms and $d\mathcal{N}_{inj}/dt = 1.2\,10^{24}$ atoms/s for t = 1-3 ms.

The diffusion coefficients are also changed in this series. The experimental measurements of density and temperature are not detailed enough to allow any inference of the diffusion coefficients profiles. Nevertheless the SXR emission, measured along chords, shows that a cold front propagates from the plasma edge to the plasma center starting at 0.7 ms and that the central temperature finally collapses at 1.5 ms. The MHD activity also strongly rises around t=1.5 ms. In addition the CO_2 interferometer measures the integrated electron density along two vertical cords crossing the plasma at R = 1.200 and 1.785 m (magnetic plasma center at R= 1.710 m) and provides information on the magnitude and distribution of the electron density increase.

For studying the influence of the loss of confinement on the F_{eff}, χ_e was changed from the profile of the steady state discharge to values of 100 - 10000 m^2/s constant over the plasma surface at t = 1.5 ms from start of injection. $\chi_e = 1000$ m^2/s causes a thermal quench duration similar to the one experimentally observed. The effect of the energy quench would be to stop the ionization of the neutrals and to decrease F_{eff} if it started before most of the particles have reached the plasma. In our case the thermal quench begins after most of the injected gas has reached the plasma and does not have a significant influence on the maximum F_{eff} achieved during the 3 ms.

The F_{eff} at 3 ms is 42 % and is in agreement with the increase of the total number of electrons inferred from the CO_2 data. The exact time behavior of the line integrated density could not be exactly reproduced even by varying profile and magnitude of the particle diffusion coefficient (D_e = 0.1 - 100 m^2/s). This issue will be the subject of further work.

Summary. These first series of simulations of massive gas injection, performed with the 2D fluid code SOLPS, shed light on the relevant mechanisms limiting the fuelling efficiency. The predicted values of F_{eff} are in agreement with the experimental measurements; its dependence on the amount of injected gas, on the gas species and valve position are explained. The injected neon carries many electrons and is potentially a candidate for raising F_{eff} above 100 %. Nevertheless its strong cooling effect keeps the electron temperature at few eV, its average degree of ionization is close to 1 and the resulting F_{eff} is around 20-40 % for $\mathcal{N}_{inj}$ = 0.4 - 1 barl.

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References.

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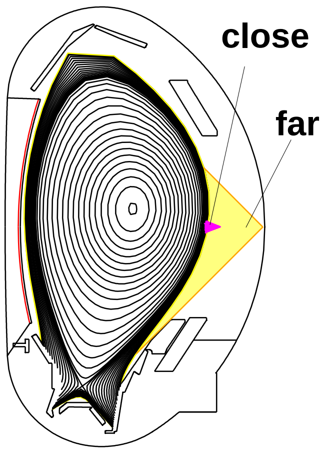
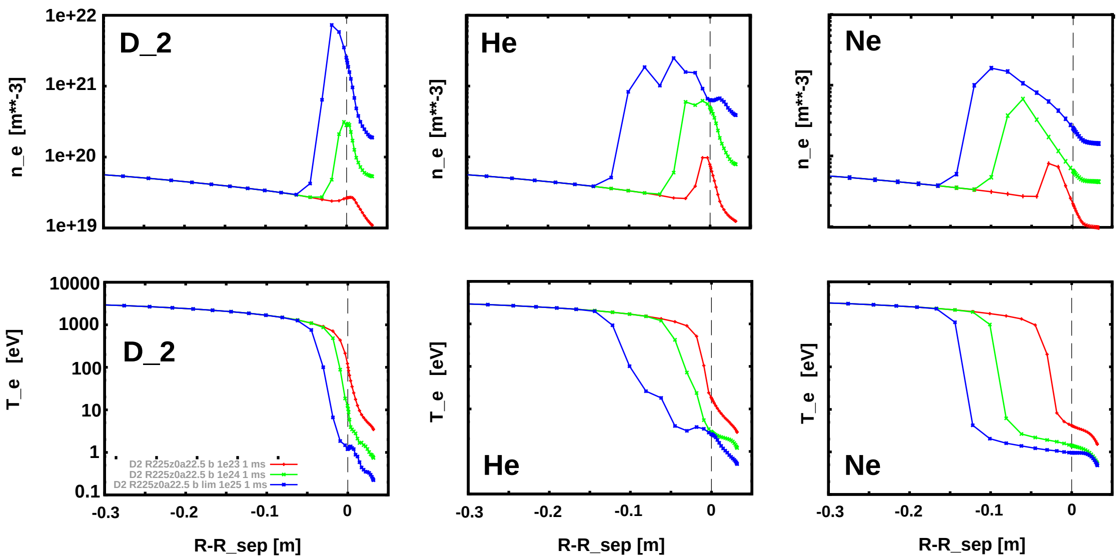


Figure 1 (left). Target plasma and two valve configurations ("close" and "far").

Figure 2 (below). Profiles of n_e and T_e at t=1 ms for D_2, He , Ne and N_inj = 10^{23} (red), 10^{24} (green) and 10^{25}(blue curve) atoms/s.



Δt = 3 ms	D_2 "close"	D_2 "far"	He "close"	He "far"	Ne "close"	Ne "far"
10**23 atoms / s	**47 %**	—	**153 %**	—	**210 %**	—
10**24 atoms / s	**37 %** **Δt = 1 ms**	**34 %**	**91 %**	**84 %**	**92 %**	**51 %**
10**25 atoms / s	**25 %** **Δt = 1 ms**	—	**35 %**	—	**29 %**	**18 %**

Table 1. Dependence of the fuelling efficiency on the flow rate and type of gas and on the valve position.