Simulations of the gas evolution during MGI

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Heat and mechanical loads accompanying disruptions can severely damage fusion devices, thus they need to be mitigated. A good candidate to mitigate a disruption is the injection of a massive amount of a medium Z noble gas (MGI), which can cool the plasma by radiation. Experimental studies are being performed on several tokamaks to optimize the gas penetration as well as the fuelling efficiency, however a proper description of the gas penetration and expansion is still missing. Even though models are developed based on quite different assumptions, they assume a prescribed poloidal and toroidal (symmetric) impurity profile [1, 2].

In this paper we present a model developed to describe the radial gas penetration at ASDEX Upgrade, when gas jets are injected at a rate larger than 10^{24} particles/s. Gas valves are situated as close to the plasma as is technically possible, thus the size of the gas jet reaching the plasma edge is at least 10x10 cm while its velocity is the ion sound speed at room temperature ($T_{flow} \sim 25\,meV$): $c_s = \sqrt{\frac{2\cdot k_B\cdot T_{flow}}{m_{ion}}}$, m_{ion} is the ion mass.

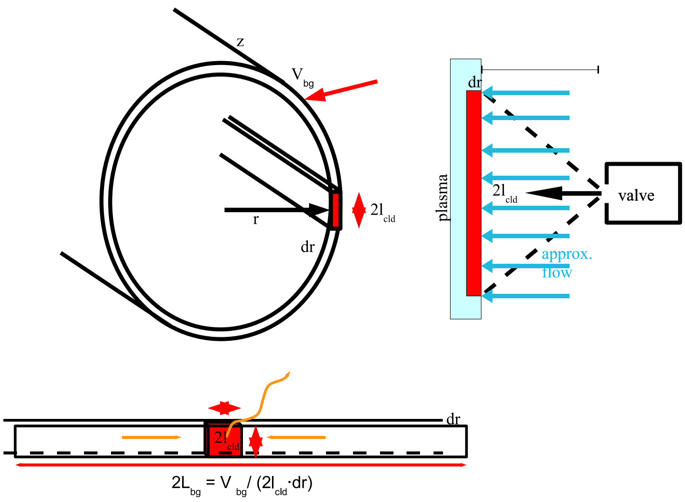

Figure 1: A sketch of the radial penetration of the gas: r refers to the radial direction, while z to the toroidal one.

The interaction of the gas with the plasma is a complex fully 3D phenomena, but here we use a simplified model. A 1D beam model is used to describe the radial neutral penetration into the plasma, overestimating the penetration of these particles as it will be discussed later. The strength of the beam is reduced by ionization, the radial penetration of the resulting ions is treated by a 1D diffusion model. We will refer to these two models as the radial model. On the other hand the electron temperature inside the partially ionized gas cloud is determined by the dynamics of the cloud itself and by the toroidal free electron flux of the background plasma in the collision-less limit and by the Spitzer theory in the collisional limit. The model including these procedures is named as the toroidal two-cells model.

The neutral gas reaching the plasma edge interacts with the background plasma electrons and it starts to get ionized. This process is very quick, as electrons inducing the ionization travel almost freely along the magnetic field lines. Ionization is accompanied by large radiation as well as by energy extraction from the background plasma. The ionized particles are stopped by the magnetic field at a distance in the order of $dr \sim 1$ cm corresponding to the ionization length of the gas, thus a gas cloud is formed having the dimensions of $(2 \cdot l_{cld}) \cdot (2 \cdot l_{cld}) \cdot dr$. This way all these processes take place in a shell limited by the two neighboring flux surfaces separated by the ionization length (see Fig. 1). The quick processes in the flux shell can be represented by the two-cells model. This model was implemented in a computational module calculating the evolution of the electron temperature of the gas cloud and of the background plasma.

On the other hand neutrals are not stopped by the magnetic field, they are assumed to penetrate further towards the plasma center with their sound speed. Besides, ions are also transported to the plasma center by anomalous diffusion. This cross field motion is much slower than the toroidal processes, thus it allows to separate the radial model from the toroidal one. The cross field ion and electron motion described by the diffusion equation is implemented in a 1D radial computational module.

To calculate the electron temperature of the gas cloud which determines the ionization rate as well as the radiative properties of the gas cloud we use a two-cells model. To apply a two-cells model the flux shell has to be considered as a flux tube having a length of $2L_{bg} = V_{bg}/(2l_{cld} \cdot dr)$, where $2l_{cld}$ is the poloidal extension of the gas cloud, while dr is the ionization length. Assuming that energy exchange takes place at the cloud-plasma surface, the two energy balance equations referring to the electrons of the gas cloud and of the background plasma are solved simultaneously. Thus, the cloud temperature T_{cld} is given by:

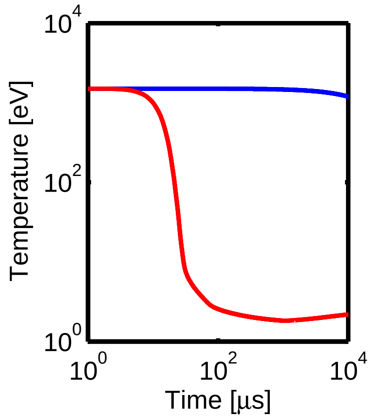

Figure 2: The time evolution of the background plasma electron temperature is plotted in red, while the temperature of the cloud is plotted in blue.

$$\int_{V_{cld}} \frac{dE_{cld}}{dt} dV = -\int_{V_{cld}} \left(P^{cld}_{\text{ion}} + P^{cld}_{\text{Br}} + P^{cld}_{\text{line}}\right) dV + \int_A \vec{q}_{\parallel,cld} \cdot d\vec{A} \tag{1}$$

while the background plasma electron temperature T_{bg} drops according to:

$$\int_{V_{bg}} \frac{dE_{bg}}{dt} dV = \int_A \vec{q}_{\parallel,bg} \cdot d\vec{A} \tag{2}$$

The electron density of the background plasma n_{bg} is assumed to be constant in time n_{bg}, while the electron density of the cloud n_{cld} is increasing due to ionization and is determined by the particle conservation in the cloud, which expands with the ion sound speed.

The cloud electron temperature which is originally equal to the background plasma electron temperature is reduced by ionization P^{cld}_{ion} and radiation $P^{cld}_{br} + P^{cld}_{line}$ losses as well as by the dilution of the electrons originating from the ionization. Cloud expansion causes energy losses as well, while the energy source of the cloud is the heat flux reaching the cloud-flux tube surface (A).

Ionization losses are calculated by the rate equations, while radiation losses based on ADAS data. The heat conduction in the collisional limit is given by:

$$\chi \frac{d(k_B T(t,z))}{dz} = -q^{hc}_{\parallel}(t,z) \tag{3}$$

where χ is the Spitzer conductivity: $\chi = 3.2\frac{nk_BT}{m_e}\cdot\tau_e = 3.2\frac{nk_BT}{m_e}\cdot\frac{3}{4\sqrt{2\pi}}\frac{\sqrt{m_e}(k_BT_e)^{3/2}}{ne^4\ln\Lambda}$. Owing to the large temperature gradient the heat conduction is heat flux limited $q_{\|}^{lim} = \gamma_{fl}2n_{bg}k_BT_{bg}v_T$, where $v_T = \sqrt{\left(\frac{8\cdot k_B\cdot T_{bg}}{m_e\pi}\right)}$ and $\gamma_{fl}\sim 0.3$. Thus $q_{\|} = min(q_{\|}^{lim}, q_{\|}^{hc})$. A typical case of the cloud and background plasma electron temperature variations are shown in Fig. 2. In this case we assumed that Neon is injected at typical ASDEX Upgrade conditions ($T_{bg} = 1500\ eV$, $n_{bg} = 1e19\ m^{-3}$ and $2L_{bg} = 1000\ m$) at a rate of $10^{24}\ Ne/s$. The particle injection is stopped after 1 ms in the simulations. As particles enter the flux tube both the background and cloud temperature are dropping. Naturally the drop is much larger in the cold and dense gas cloud. When the cloud density becomes large enough the temperature drop basically stops, but later on due to the continuous energy input the cloud temperature start to slightly increase. The rate of temperature increase in this case is determined by the balance between ionization-recombination and expansion.

In the second model we assume a single gas cloud cell in the toroidal direction and we calculate the radial neutral penetration according to the equation of motion and the radial ion penetration according to the Fick's law. In the present approach, the gas cloud expansion in poloidal direction is neglected, so the heat diffusion equation simplifies as:

$$\frac{\partial n_{cld}^{i,e}(r,t)}{\partial t} + \frac{\partial}{\partial r}\left(D\frac{\partial n_{cld}^{i,e}(r,t)}{\partial r}\right) - S^{i,e}(r,t) = 0 \qquad (4)$$

where $n_{cld}^{i,e}$ is the density of the i-th ionization state or of the electrons and $D = 1\ m^2/s$ is the anomalous diffusion coefficient. $S^{i,e}$ represents the source and sink due to ionization and recombination. Eq. (4) is solved explicitly by centered discretization method. To illustrate the results of this model we assume a constant cloud temperature of 2 eV and a constant, continuous neutral gas input rate of $10^{24}\ Ne/s$. The diffusion takes place here on a distance of 1 m and the source is situated at the middle of the computational regime. The distribution of the different ionization stages are shown in Fig. 3 at 500 μs.

To simulate an experimental scenario the two modules are combined. The gas cloud temperature is calculated by the toroidal two-cells model and radial cloud penetration by the 1D diffusion model for a typical ASDEX Upgrade H-mode discharge (#20043). In the presented case we performed the simulations for 1 ms assuming again Neon injection at a constant rate of 10^{24} Ne/s. The results of the simulations are shown in Fig. 4 and Fig. 5.

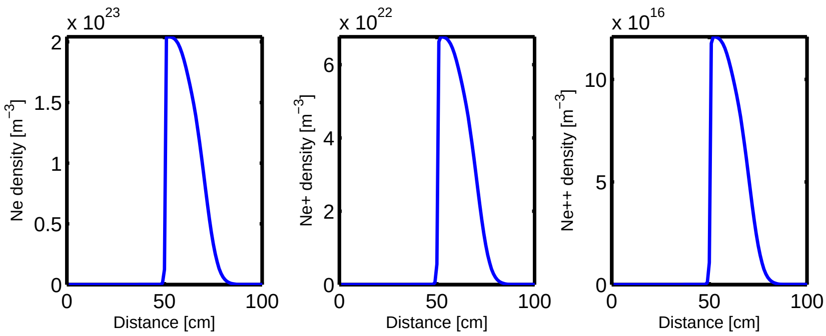

Figure 3: Ne, Ne+, Ne++ density profiles at 500 μs (input rate $10^{18}\ Ne/\mu s$).

The neutrals penetrate the plasma with $\sim$ 500 m/s, thus after 0.3 ms they reach half of the minor radius and after 1 ms they reach the plasma center (see the number of Ne in Fig. 4). Besides the electrons of the partially ionized gas cloud cool down to a few eV, thus a large population of Ne^{+} and Ne^{++} is also present as is shown in Fig. 4. In experiments, neutrals cannot be observed in the plasma center, as the neutral-ion collision slows down the neutrals. Charge exchange can also change the neutral gas penetration and accordingly the distribution of the different ionization stages.

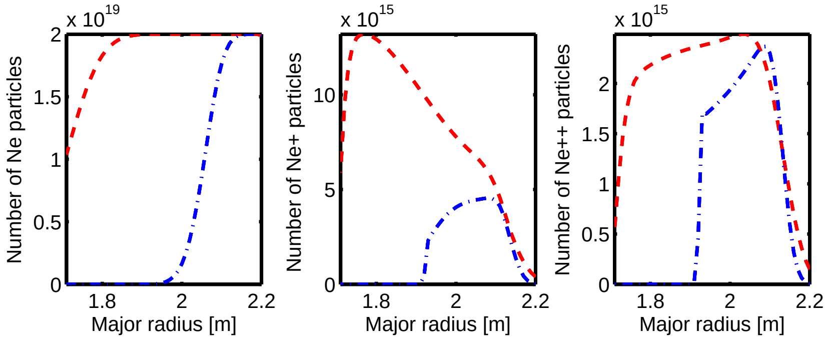

Figure 4: The profile of Ne, Ne+, Ne++ at 0.3 ms (blue) and 1 ms (red) for a typical AUG discharge, assuming a source rate 10^{18} $Ne/\mu s$.

In Fig. 5 we plot the temperature profile of the background plasma (left) and of the cloud (right) at 0 ms, 0.3 ms and 1 ms. Because of the flux limited energy transfer between the cloud and background plasma, the background plasma cools slowly, after 1 ms its central temperature is still far above 1 keV. The background plasma temperature drops to a few hundreds of eV only after 3-5 ms. This is close to the experimental observations, which shows that the thermal quench occurs after 2 ms.

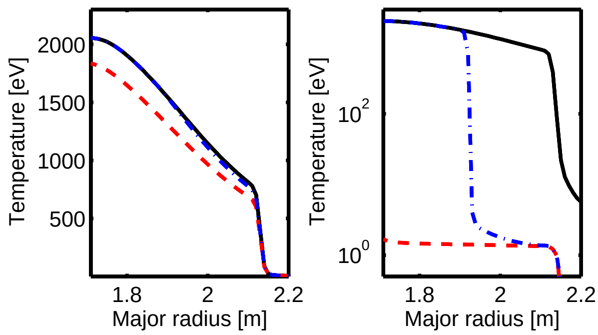

Figure 5: The initial electron temperature profile (black), the temperature profile of the gas cloud (right) and of the background plasma electrons (left) after 0.3 ms (red) and 1 ms (blue)

We can conclude, that such a simple model can only roughly reproduce the experimental findings. A more important aspect is to model the toroidal expansion of the gas cloud evolution in detail, so this model will be combined with a Lagrangian model [4] allowing to calculate the toroidal particle and radiation distribution of the cloud, but this is a subject of our future work.

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