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Energy balance during pellet assimilation

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Pellet injection is used in tokamaks and stellarators for fueling, ELM pacing and disruption mitigation. Injection of shattered pellets is a critical part of the envisaged ITER disruption mitigation system. Rapid deposition of a large amount of material is expected to result in a quick cooling of the entire plasma. However, it has recently been demonstrated that a considerable transfer of thermal energy from the electrons of the background plasma to the ions accompanies a localized material injection [1]. This is the result of the ambipolar expansion along the magnetic field line of the cold and dense plasma cloud left behind the ablated pellet. If the cloud is heated at a constant rate, the ions accelerated by the ambipolar electric field acquire half the total energy transferred to the cloud if radiation losses are negligible. If the heating source is depleted and the heating rate drops as the cloud expands, the majority of the energy is transferred to the ions.

In the present work, we investigate the role of the ambipolar energy transfer mechanism in the global plasma energy balance, in particular its role in disruption mitigation cases. In conventional mitigation scenarios, it is assumed that impurity radiation and radial heat transport in stochastic magnetic fields are the two mechanisms responsible for the dissipation of the pre-quench electron thermal energy. We show that ambipolar energy transfer is a competitive mechanism and may even dominate the electron energy balance. As a result, the thermal quench timescale is shortened compared to a uniform injection of impurities, since a part of the pre-quench electron thermal energy is transferred to the plasma ions rather than being dissipated to the wall on the thermal quench electron timescale.

The total radiation losses from a partially ionized gas are the combination of radiation in spectral lines due to electron impact excitation and dielectronic recombination, and radiation in the continuous spectrum due to radiative recombination and bremsstrahlung. Line radiation plays the dominant role in radiative losses of optically thin plasma. However, the mean free path of a line photon is typically much shorter than that of the continuum radiation. Therefore, for relatively high densities the line radiation losses can be significantly reduced due to re-absorption [2]. Continuum radiation will be the dominant energy loss mechanism is such a case.

The initially very dense pellet cloud is not transparent to line radiation and radiates predominantly in the continuous spectrum. The cloud transitions to volumetric line radiation as it expands and becomes optically thin for the lines.

Figure 1 shows the breakout of the electron, ion and the total coupled energy for an expanding dense Argon cloud heated by ambient electrons that cool down during the cloud expansion in accordance with total energy conservation. The plasma and the pellet parameters are relevant to tokamak disruption mitigation scenarios, and heat conduction along stochastic field lines is assumed to be negligible. The details of the pellet ablation process are not considered as we assume fast localized material deposition on a field line as the initial condition for the subsequent ambipolar expansion. These results are obtained by solving hydrodynamic equations for the expansion of the dense plasma cloud (see Ref. [1]) taking into account continuum radiation losses according to the atomic radiation data from Ref. [3]. The cloud drifts due to magnetic field inhomogeneity are also neglected.

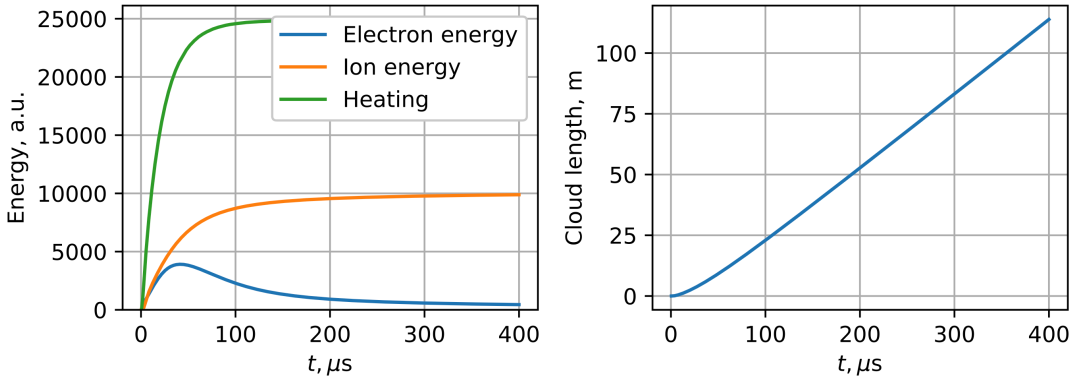

Figure 1: Evolution of the electrons and ions energy during the pellet cloud expansion along the field line taking into account radiation losses. The total energy coupled to the cloud by the background plasma is shown with the green curve. This energy saturates at about 100 μs as the ambient plasma cools down. The longitudinal size of the cloud is shown on the right panel.

For the case shown in Fig. 1 approximately 40% of the total pre-quench electron energy stored on a field line is transferred to the pellet ions and the rest is eventually radiated. The effective size (length) of the cloud along the field line is also shown in Fig. 1.

The relative amount of radiated energy and energy deposited in the ions is found to be sensitive to the initial cloud density and the heating rate. For instance, the ions get 60% of the total energy if the initial cloud density is half as high as in Fig. 1 (assuming the same per-particle heating rate).

The ambipolar electron-ion energy transfer mechanism should be taken into account in the design of the ITER disruption mitigation system [4]. The pre-quench electron energy transferred to ions will eventually be dissipated but on a longer timescale. At the same time, the thermal quench timescale is shortened by this mechanism, and the radiated energy is toroidally localized.

References

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