Energy balance during pellet assimilation

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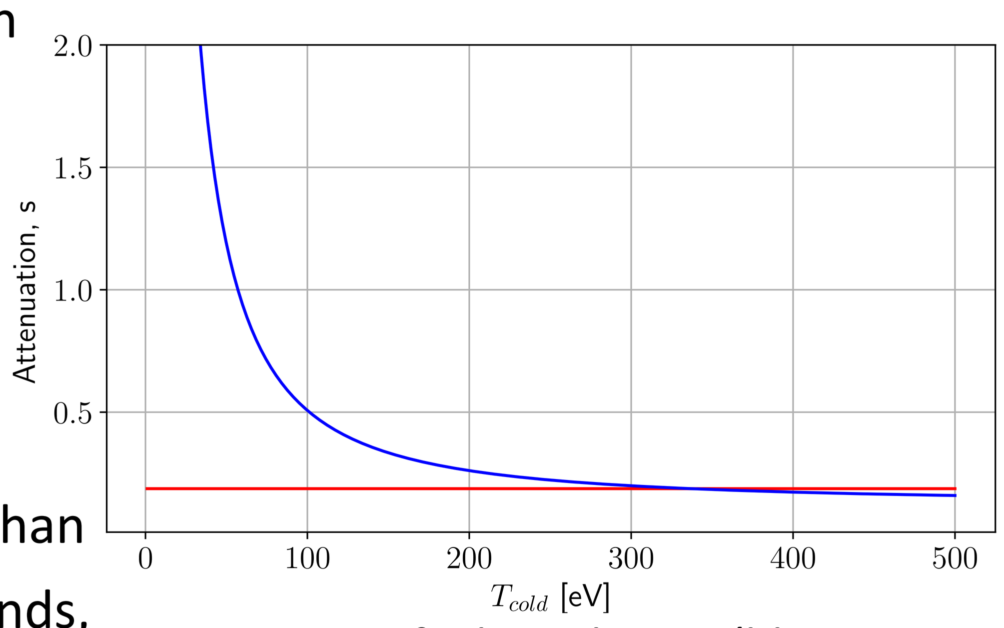
ABSTRACT

- 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 controlled cooling of the entire plasma. Unlike in the case of uniform gas injection, a considerable transfer of thermal energy from plasma electrons to the injected ions accompanies a localised material injection, due to ambipolar parallel expansion of the pellet produced plasmoid.
- The present work quantifies this energy transfer.

GENERAL CONSIDERATIONS

- The cold plasmoid opacity is different for ambient hot electrons and ions.
- The hot ions stopping power on cold electrons is very high, so that the cold plasmoid is not transparent for these ions and experiences their pressure.
- Plasmoid pressure evolves as $t^{-1/2}$ and is typically higher than the ambient initially. As it expands, its pressure decreases and becomes comparable to the ambient pressure. Yet, a heated plasmoid is transparent for the ambient ions and the momentum exchange vanishes.

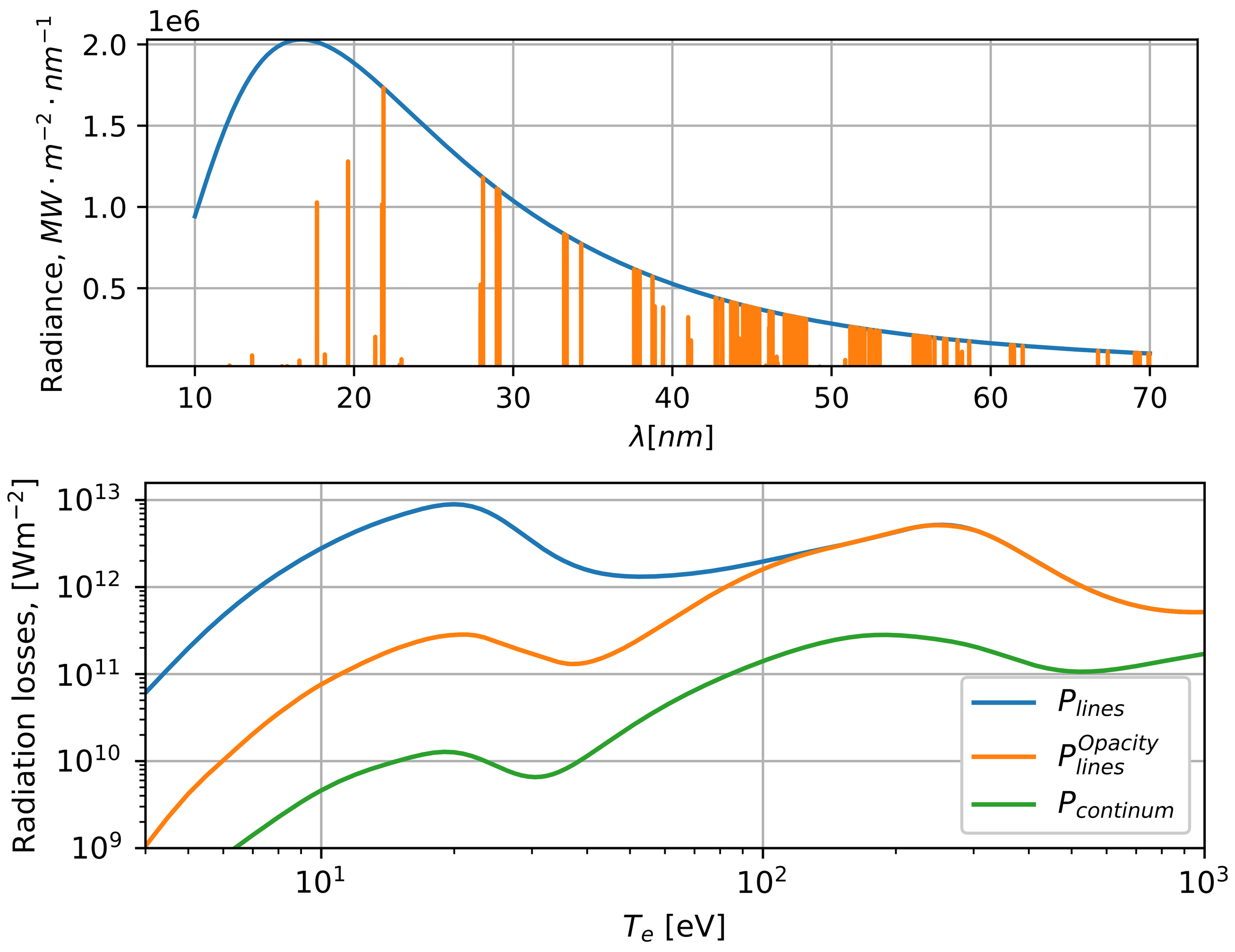


Attenuation of 5 keV plasma (blue - ions, red - electrons) in $2 \cdot 10^{22} m^{-2}$ plasmoid.

- Thus, expansion of a pellet-produced plasmoid can be treated as an expansion into vacuum.
- The plasmoid ion temperature remains low during the entire expansion.
- Ambipolar potential $e\phi \approx T_{cold} \ln\left(\frac{n}{n^a}\right)$ becomes comparable to T_{hot} and can affect the ambient plasma (not taken into account in this work).

RADIATION LOSSES

- In plasma with high-Z impurities radiation is dominated by line radiation.
- The optical thickness is different for different types of radiation.
- The mean free path of a resonant photon in the line radiation process can be significantly shorter than the width of the plasmoid.
- Upper estimate: spectral radiance of any radiation cannot exceed that of a black body. We cut every line at Planck's law level, assuming Doppler broadening mechanism.
- The resulting radiation losses are reduced significantly for T < 100 eV.



Model spectrum intensity (from a unit surface) of a 10 cm slab of Argon plasma with $n_i = 10^{22} m^{-3}$ at 15 eV (top). Radiated power loss of a corresponding plasma layer (bottom).

SELF SIMILAR PARALLEL EXPANSION

GOVERNING EQUATIONS

- Expansion of a heated plasmoid is governed by the following system of hydrodynamic equations

$$\frac{\partial n}{\partial t} + \frac{\partial (nu)}{\partial x} = S\delta(x),$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + \frac{ZT}{m_i}\frac{\partial \ln n}{\partial x} = 0,$$

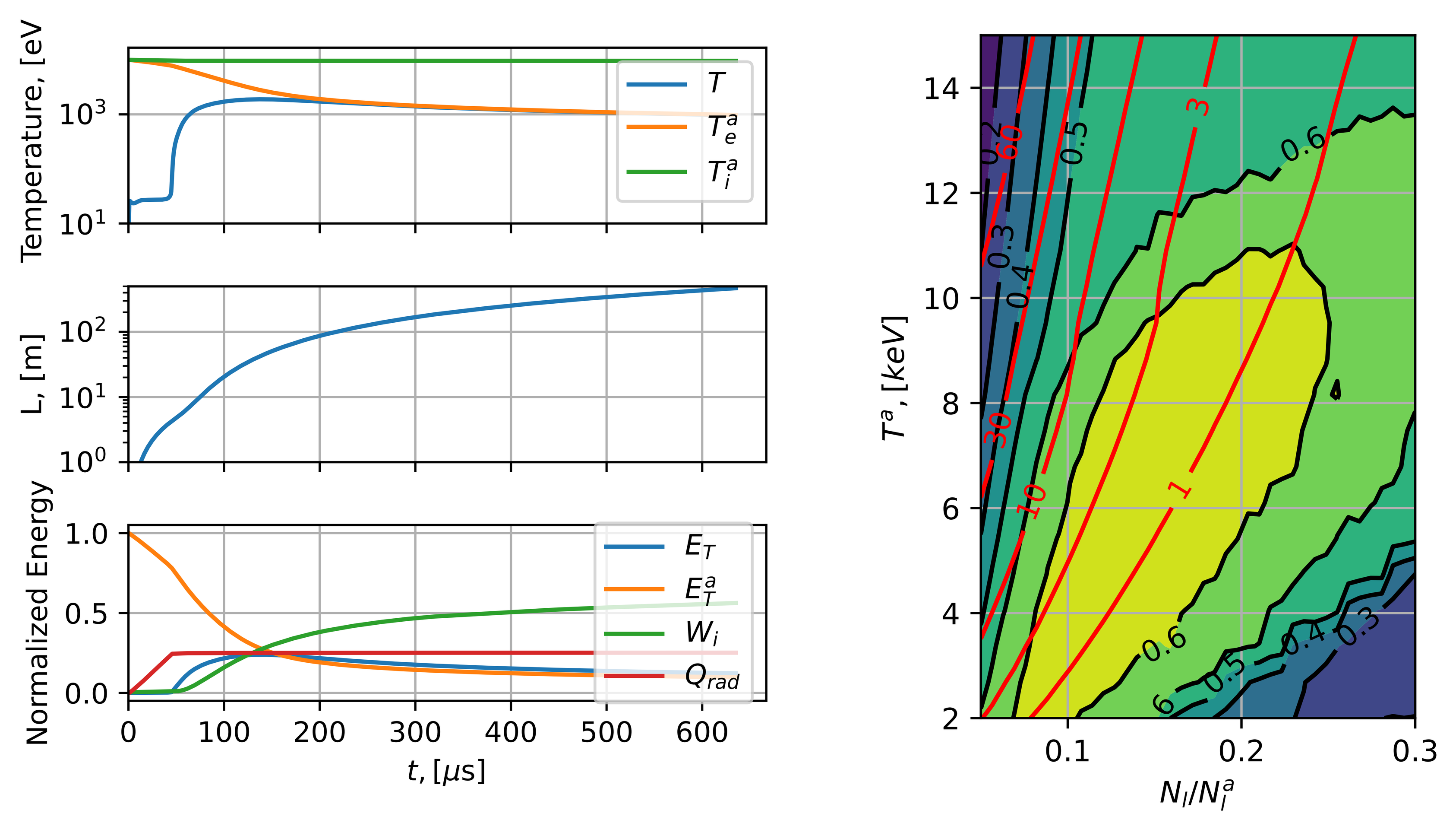
$$\frac{3}{2}\frac{d}{dt}\int nZTdx + \frac{m_i}{2}\frac{d}{dt}\int nu^2 dx = P_{heating}(t) - P_{rad}(t),$$

which admits a self-similar *Ansatz* $n = N_l\sqrt{\frac{a(t)}{\pi}}\exp\left(-a(t)x^2\right)$, $u = b(t)x$ for $S = 0$. This Ansatz used below to calculate the expansion.

- Self-similar solutions obtained for $n(0) = \text{const}$, $S = \text{const}$ and $S \sim \sqrt{t}$ (see [Arnold, A.M., Aleynikov, P., Helander, P., Self-similar expansion of a plasmoid supplied by pellet ablation, Under consideration in PPCF (2021)])

RESULTS

- Figure shows evolution of a neon plasmoid. The energy balance for the hot plasma is modelled approximately as $\frac{3}{2}\int_0^A n^a \dot{T}^a dx = -Q_{heating}$.
- Temperature stays at ≈20 eV initially as the strong line emission radiates the incoming energy (despite the plasmoid is not transparent for lines).
- After expanding to about 10 m, the radiation losses decrease (due to density decrease $\sim t^{-3/2}$) so heating and expansion accelerate. Ultimately the ions gain over 50% of the pre-pellet electron thermal energy (W_i).
- The ambipolar energy transfer accounts for up to 60% of the electron thermal energy (right figure), the remainder is radiated in the beginning.
- Eventually all the ion energy is radiated as well. At this point the plasma is homogeneous and the ion energy radiation is on the ion thermalisation timescale shown with red contours.



Evolution of a neon plasmoid with $N_l = 10^{22} m^{-2}$ in an ambient plasma of 10 keV and $10^{20} m^{-3}$. Ultimate ion energy as a function of pre-pellet temperature and the amount of assimilated Neon atoms. The red contours indicate ambient ions thermalisation time in a post pellet plasma in ms.

CONCLUSION

- Significant transfer of pre-quench electron thermal energy to the injected ions is expected for the disruption mitigation pellets.
- The remainder of the energy is radiated by a dense plasmoid during expansion, in spite of the line emission trapping.
- The ion energy and the energy transferred to the injected ions are expected to be radiated on a longer timescale after homogenisation.