Assimilation of a Composite Hydrogen/ High-Z Plasmoid

Pavel Aleynikov[1], Alistair M. Arnold[1], Boris N. Breizman[2], Per Helander[1], Alexey Runov[1]
[1]Max-Planck-Institut für Plasmaphysik,
[2]Institute for Fusion Studies, University of Texas

MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

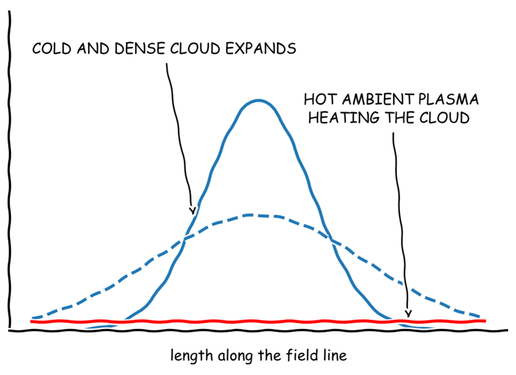
IFS

MOTIVATION AND SETUP

- 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 plasma. The dense pellet-produced plasmoid undergoes ambipolar expansion with a considerable transfer of electron thermal energy to the ions.
- High density of the plasmoid increases radiation in presence of high-Z impurities. The plasmoid may become optically thick for line radiation.
- The present work quantifies energy balance during plasmoid assimilation.
- Not considered: self-consistent ablation process, plasmoid drifts

*The case of slow pellets is considered in [Arnold, A.M., Aleynikov, P., Helander, P., Self-similar expansion of a plasmoid supplied by pellet ablation, Accepted to PPCF (2021)]

- Consider a fast* pellet that crosses a field line
- Only a thin layer (~ mean free path) is heated and evaporated by the plasma heat flux
- This evaporated dense gas cloud expands with the sound speed in three dimensions. The 3D expansion stops when the cloud becomes ionized and its hydrodynamic pressure becomes lower than the magnetic pressure
- Subsequently, the cloud expands along the field line



EXPANSION OF A HEATED PLASMA INTO VACUUM

- In the simplest case of cold plasmoid ions and constantly heated electrons the expansion is governed by the hydrodynamic equations:

$$\frac{\partial n}{\partial t}+\frac{\partial}{\partial x}(nu)=0,$$

$$m_i\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}\right)=-T(t)\frac{\partial \ln n}{\partial x},$$

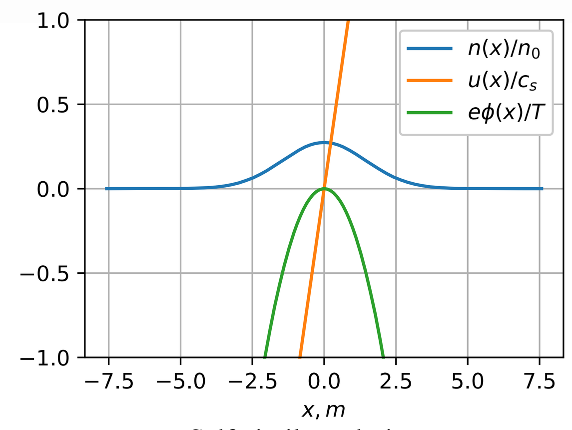
$$\frac{d}{dt}\int_{-\infty}^{\infty}\left(\frac{3nT}{2}+\frac{m_i n u^2}{2}\right)dx=\int_{-\infty}^{\infty}Q(t)n\,dx$$

- with a solution [1]:

$$n(x,t)=n_0\sqrt{\frac{3m_i}{8\pi\tau t^3}}\exp\left(-\frac{3m_i x^2}{8\tau t^3}\right),$$

$$u(x,t)=\frac{3x}{2t},$$

$$T(t)=t\tau,\quad \tau=\frac{1}{3n_0}\int_{-\infty}^{\infty}nQ\,dx\,.$$



Self-similar solution

Half of the energy transmitted to the plasmoid by the ambient plasma is in the kinetic energy of the plasmoid ions

[Aleynikov, P., Breizman, B., Helander, P., Turkin, Y. 2019 Plasma ion heating by cryogenic pellet injection, Journal of Plasma Physics, **85**, 905850105.]

ELECTRON KINETICS IN AN AMBIPOLAR POTENTIAL

- Plasmoid electrons are confined by a potential well.
- Passing ambient electrons arrive from infinity, pass through the well, and escape to infinity.
- The short mean free path approach is inappropriate for electrons. Instead, a bounce-averaged kinetic equation describes the adiabatic change in electron energy and collisions

$$\frac{\partial f}{\partial t}-e\frac{\overline{\partial \Phi}}{\partial t}\frac{\partial f}{\partial E}=\overline{C(f)}$$

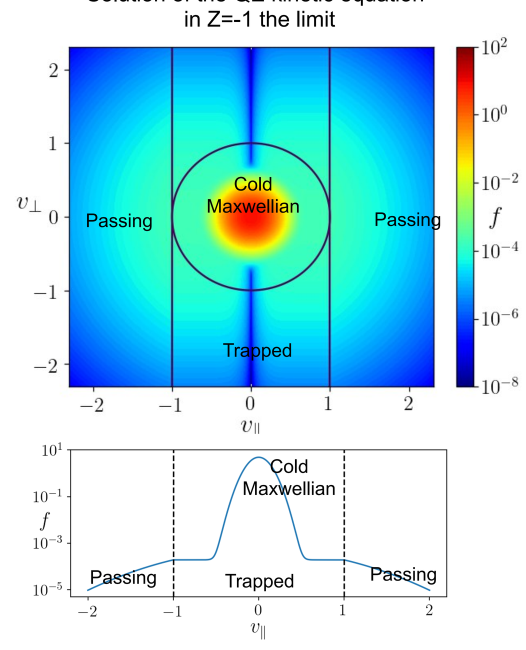
- Since self-collisions are faster than well expansion, a near-stationary distribution function is established on the self-collision timescale; the distribution solves

$$\overline{C_0(f)}=0$$

requiring that the entire electron distribution is continuous.

- The trapped and passing electrons form a non-Maxwellian quasi-equilibrium (QE) state.

Solution of the QE kinetic equation in Z=-1 the limit



PROFILES OF A COMPOSITE PLASMOID

- Equation of motion for Neon ion in an expanding plasmoid

$$M\ddot{x}=eZE+\frac{dp_\alpha}{dt}$$

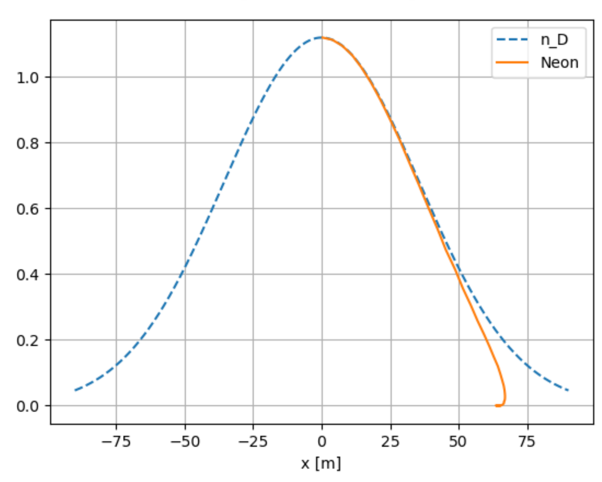
- The friction force of a particle with energy E_α in a plasma with temperature T_β:

$$\frac{dp_\alpha}{dt}=-m_\alpha v_\alpha\left(\frac{1+\frac{m_\alpha}{m_e}}{\tau_1^\alpha}\mu(x^{\alpha/e})+\frac{1+\frac{m_\alpha}{m_i}}{\tau_1^\alpha}\mu(x^{\alpha/i})\right)\sim\frac{1}{v_\alpha^2}$$

- with the collisional time $\tau_1^{\alpha/\beta}=\frac{\sqrt{m_\alpha}}{\pi\sqrt{2}e_\alpha^2 e_\beta^2}\frac{E_\alpha^{3/2}}{n_\beta \ln\lambda}$, and $x_\beta=\frac{m_\beta}{m_\alpha}\frac{E_\alpha}{T_\beta}$.

- Solving for a Ne^+ ion in 10^{22} m^{-2} H plasmoid using the self-similar solution for H shows that most of the Neon expands together with H.

Plasmoid density profile and the positions of Ne^+ test-particles after expansion



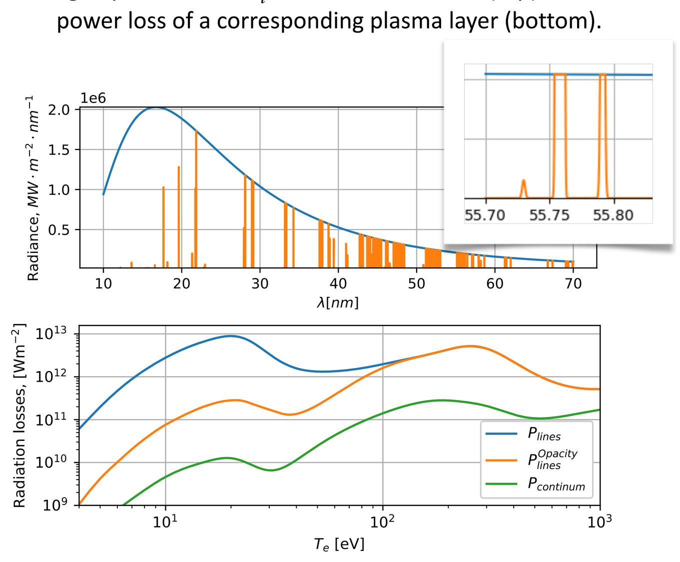
RADIATION LOSSES

- Line radiation dominates in a plasma with high-Z impurities.
- The photon mean free path in the line radiation process can be significantly shorter than the width of the plasmoid (~10 cm).
- 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.

$$P_{rad}\approx\int\min\left(\sum_l n_i^{k_l}n_e\varepsilon_l\frac{hc}{\lambda}P_l(\lambda)r_p, B(\lambda)\right)d\lambda$$

- The resulting radiation losses are reduced significantly for T < 100 eV.
- NB. Collisional radiative model is not applicable at high densities (lines trapping is not accounted for).

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).



GOVERNING EQUATIONS

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

$$\frac{\partial(n_D+n_i)}{\partial t}+\frac{\partial((n_D+n_i)u)}{\partial x}=0$$

$$\left(n_D M_D+n_i M_i\right)\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}\right)=T\frac{\partial(n_D+Zn_i)}{\partial x}$$

$$\frac{3}{2}\frac{d}{dt}\int(n_D+n_iZ)T\,dx+\frac{1}{2}\frac{d}{dt}\int(n_DM_D+n_iM_i)u^2dx=-L(T)\int n_i(n_D+n_iZ)dx+Q(t)\int(n_D+n_iZ)dx$$

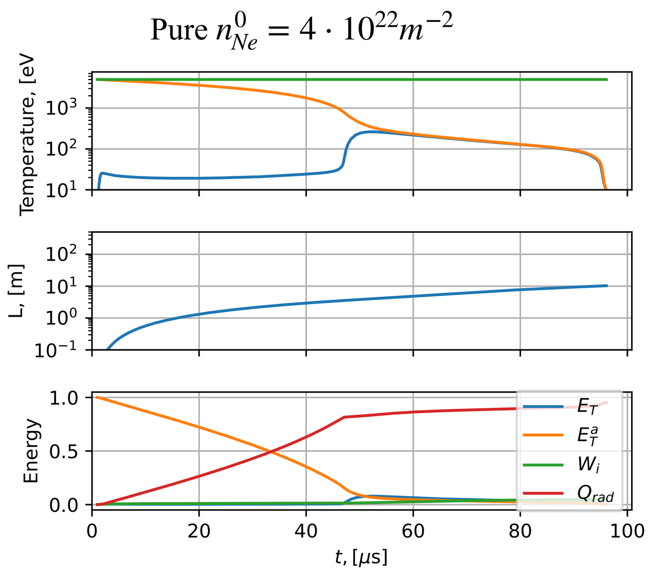
- The equations admit a self-similar Ansatz $n=N_l\sqrt{\frac{a(t)}{\pi}}\exp\left(-a(t)x^2\right)$, $u=b(t)x$ for $S=0$.
- $P_{heating}$ is given by the collisional energy exchange between the ambient plasma and the plasmoid
- The ambient temperature evolution is approximated using $\frac{3}{2}\int_0^A n^a\dot{T}^a dx=-Q_{heating}$

where A is the field line length. We assume that the field line covers the flux surface. The cases of short connection length on rational magnetic surfaces are ignored.

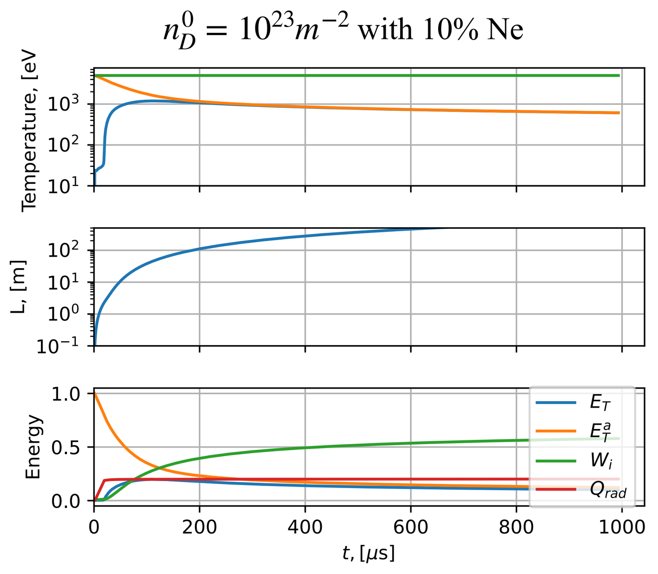
RESULTS OF ASSIMILATION CALCULATION

- Ambient plasma $T_{hot}=5$ keV and $n_{hot}=10^{20}m^{-3}$; Plasmoid size $L_\perp=10$ cm; $N^0/N_{hot}=0.5$

Pure $n_{Ne}^0=4\cdot10^{22}m^{-2}$

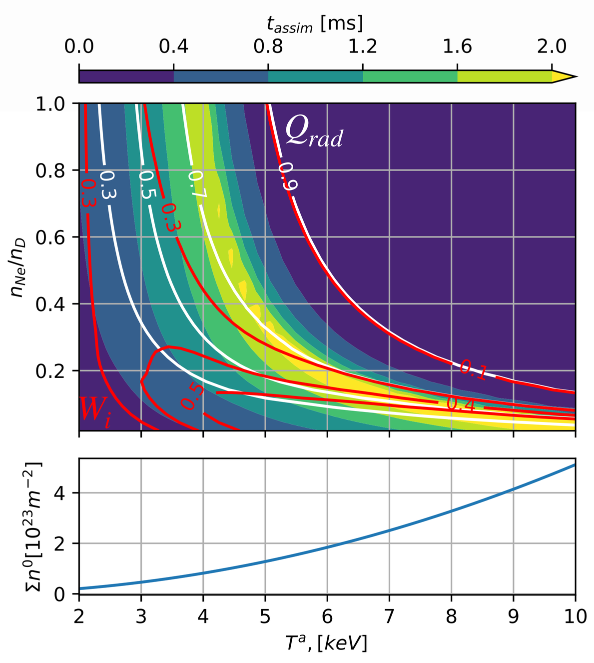


$n_D^0=10^{23}m^{-2}$ with 10% Ne



SUMMARY

- Impurity admixture density follows the H density profiles during expansion
- Kinetic effects may reduce heating rate (under consideration)
- Plasmoid is not transparent to line-radiation
- At low temperature, homogenization is faster than thermalization
- The ambipolar energy transfer to the ions accounts for up to 50% of the electron thermal energy in the low impurity content cases. This energy is radiated on a longer timescale
- High impurity concentration leads to radiative energy loss from the entire flux surface on the electron collisional timescale



This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

EUROfusion