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Pellet Ablation Physics Studies for Disruption Mitigation

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ABSTRACT

This work addresses three aspects of the pellet-plasma interaction physics:

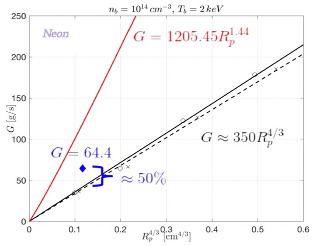
- We provide a first-principle kinetic theory for the hot electron energy deposition into the high-Z pellets. Our theory predicts a substantial reduction of the pellet ablation rate in comparison with pre-existing estimates by other authors.
- We show how the electrostatic field at the pellet-plasma interface maintains the low-Z pellet charge neutrality by creating an outgoing cold electron beam in response to the incident flux of the hot electrons.
- We explain the rapid sublimation of a pellet irradiated by runaway electrons, which is in line with the observations in DIIID.

ABLATION RATE FOR HIGH-Z PELLETS

For high-Z pellets, the velocity distribution of the hot electrons is nearly isotropic, and we use this feature to simplify and solve the electron kinetic equation, including the effect of electron gyro-motion in a magnetic field The resulting ablation rate for the high-Z pellets can be estimated as [1]

$$G \sim \frac{4\pi M}{\left(\pi e^4\right)^{2/3}} \left(\frac{1}{m^{1/2} M}\right)^{1/3} R_p^{4/3} \frac{n_\infty^{1/3} T_\infty^{11/6}}{Z^{7/6} \left(\ln \Lambda_{ei}\right)^{1/2} \left(\ln \Lambda_{ee}\right)^{1/6}}$$

Here, e and m are the electron charge and mass, M is the ion mass, R_p is the pellet radius, n_∞ and T_∞ are the density and temperature of the ambient electrons, and $\ln \Lambda_{ei}$ and $\ln \Lambda_{ee}$ are Coulomb logarithms for elastic and inelastic collisions.



Reduction of the ablation rate due to elastic scattering. Predictions by Sergeev et al. (2006) [2] are too high. The difference between our results (black lines) and Samulyak and Parks (2019) [3] shows significant sensitivity of the heat deposition to elastic scattering.

STRONG SCATTERING REDUCES ELECTROSTATIC SHEATH

Hot electron flux into the pellet scales as $j_{hot} \sim \frac{1}{\sqrt{Z}} n_\infty \sqrt{\frac{T_\infty}{m}}$

Return flux of the emitted cold electrons satisfies the Child –Langmuir law

$$j_{cold} \sim m\left(e\varphi / m\right)^{3/2} / \left(e^2 d^2\right)$$

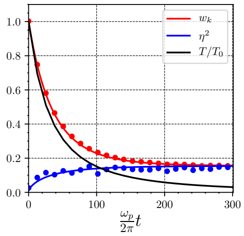
The sheath width is roughly the Debye length $d^2 \sim T_\infty / \left(n_\infty e^2\right)$

The return cold flux balances the hot particle flux, which gives

$$e\varphi \sim T_\infty / Z^{1/3} << T_\infty$$

SHEATH EFFECT ON AMBIENT ELECTRON COOLING

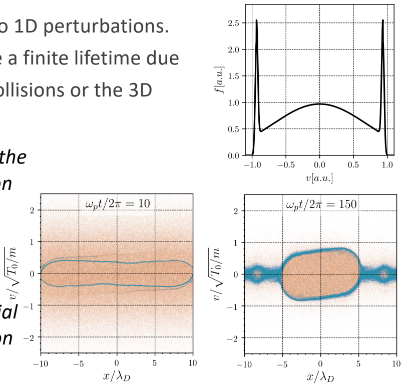
For low-Z pellets, the sheath potential traps the ambient electrons on a magnetic field line connecting the pellet's opposite sides [4]. The trapped electrons don't cool down as a result.



Ambient electron cooling due to low-Z pellet injection. Time traces of the average electron kinetic energy w_k (in red) and the normalized depth of the electrostatic potential well η^2 (in blue). Analytical estimates (solid lines) are in line with the numerical results (dots). Initially, the cooling rate follows the ideal gas estimate (black curve). The electron cooling virtually stops once the sheath is formed.

PHASE SPACE STRUCTURE FORMATION

- Trapped electrons and two counter-streaming beams form a phase space structure on a field line connecting the pellet's opposite sides.
- The phase structure preserves a significant fraction of the initial electron kinetic energy.
- The distribution is stable to 1D perturbations.
- The steady-state may have a finite lifetime due to the electron-electron collisions or the 3D effects.



The upper panel illustrates the trapped electron distribution function edged by two cold electron beams. Two lower panels show numerical snapshots of the electron phase space during the initial (on the left) and the final (on the right) colling phases.

PELLET SUBLIMATION AND EXPANSION UNDER RE FLUX

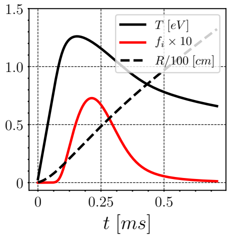
EXPERIMENTAL FINDINGS

Recent experiments show [5] that the pellet injected into the RE beam does not necessarily enhance impurity mixing vis-à-vis the massive gas injection scenario. This observation suggests that REs fully ablate the pellet near the beam's edge before any significant radial penetration can occur.

ANALYTICAL ASSESSMENT

1D analytical treatment [6] suggests:

- **Volumetric heating**: The pellets available for mitigation of the RE current in ITER are transparent for the REs with energies ~ 10 MeV.
- **Rapid sublimation**: The cryogenic pellet or its fragments will likely be sublimated instantly at the edge of the RE beam.
- **Expansion**: The sublimated pellet material spreads over the poloidal cross-section of a tokamak on a millisecond time scale. By the time it covers the poloidal cross-section, its temperature lies in a 1 eV range, and the ionization fraction stays low.



Expansion of a sublimated argon pellet ($9*10^{23}$ atoms) irradiated by runaway electrons ($n_{RE} = 10^{10}$ [cm^{-3}]). This plot presents the evolution of the cloud temperature (solid black curve), the ionization fraction (solid red curve), and the cloud radius (dashed black curve).

ACKNOWLEDGEMENTS / REFERENCES

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