Dreicer mechanism of runaway electron generation in presence of high-Z impurities

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It is expected that massive population of the runaway electrons (REs) may be generated during plasma disruptions in ITER. An uncontrolled loss of such REs can cause localized damage of the Plasma Facing Components (PFCs). Then a Disruption Mitigation System (DMS) is being developed in ITER to control or suppress RE generation. One of the most promising techniques employed in the future DMS is the injection of High-Z impurities [1].

Although the avalanche mechanism of RE production is anticipated to be the dominant mechanism in ITER [2], the avalanche multiplication of the runaways after the thermal quench (TQ) still requires a seed RE current. One of the mechanisms of RE generation recognized in the past as an important RE seed provider is the diffusive leak of electrons from the maxwellian core into the high-energy "runaway" field [3] ("Dreicer generation"). In ITER the cold post thermal quench plasma will be characterized by the large amount of partially ionized impurities.In such plasma, bound electrons as well as free electrons give contribution into the friction force of energetic electrons. This makes the problem statement on RE generation different from that in [3].

In the present work a Fokker-Planck equation for the electron distribution function is solved numerically to evaluate the Dreicer RE generation rate taking into account electron interaction with partially ionized high-Z impurities according to the model [4].

The high-energy limit of the relativistic Fokker-Plank equation considered in this work is (see, for example,[5])

$$\frac{\partial F}{\partial s}+\frac{\partial F}{\partial s}\left(E\cos\theta-1-\frac{1}{p^2}-A\left(p,T\right)-\frac{\beta(p^2+1)}{p^3}\frac{\partial F}{\partial s}\right)=$$

$$\frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\sin\theta\left(E\frac{\sin\theta}{p}F+\frac{Z+1+Zb(\mathrm{p},\mathrm{T})}{2}\frac{\sqrt{p^2+1}}{p^2}\frac{\partial F}{\partial\theta}\right)\qquad(1)$$

where p is the particle moment (normalized to mc), θ is the pitch angle, s is the time variable (normalized to $\tau=4\pi\varepsilon_0^2m_0^2c^3/e^4n_e\Lambda$), E is the electric field (normalized to $E_e=m_0c/e\tau$), $\beta=T_e/m_0c^2\ll1$. Momentum and bulk plasma temperature (*T*) dependent coefficients *A(p,T)* and $Z_b(p,T)$ represent friction and scattering on partially ionized impurities, respectively. The normalization of the distribution function is given by $\int F dp \sin\theta d\theta = 1$. The low-energy limit of the collisional integral in Eq. (1) is approximated with use of the Chandrasekhar function similarly to Ref. [6]. The effect of the synchrotron radiation on the Dreicer flow is weak and thus neglected in the current work. Equation (1) is solved numerically using FiPy Finite Volume PDE Solver [7].

We first verify our Dreicer flow calculation against the analytical formula from [3] for a case of fully ionized plasma. A good agreement has been achieved aside from the pre-exponential factor of order unity (studied in [5]). In Fig. 1 the runaway generation rate is plotted against electric field normalized to, so-called, Dreicer field $E_D = \dfrac{4\pi e^3 N_e \Lambda}{kT_e}$, for Z_{eff}=3, T=10 eV, .

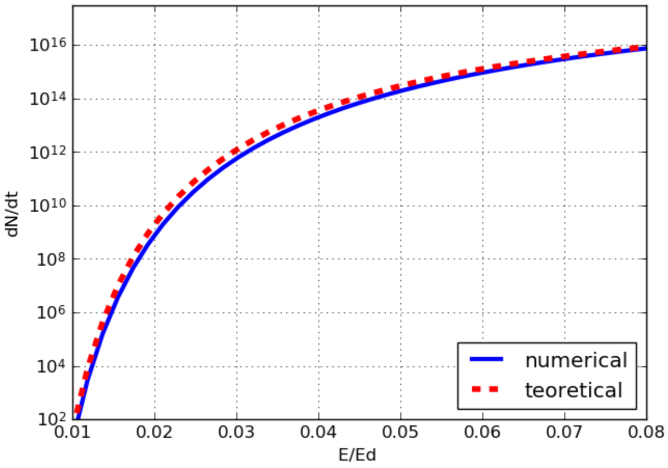


Figure 1 *Run away rates dependence on electric field*

Following the recipe of Ref. [8] we calculate the extra friction force $A(p,T)$ and scattering $Z_b(p,T)$ on partially ionized impurities according to the model [4], where the effective ion potential is determined by the Thomas-Fermi model.

In Fig. 2 we explore the effect of the “unaccounted” interaction with high-Z impurities on the distributions function by comparing calculations with and without $A(p,T)$ and $Z_b(p,T)$ terms. Figure2a shows a 2D electron distribution function for plasma with $2{\cdot}10^{19} m^{-3}$ Hydrogen and $2{\cdot}10^{19} m^{-3}$ Argon at temperature T=10 eV and electric field E=0.03E$_D$. Figure 2b shows a comparison of isotropic parts of the distributions ($\int F \sin\theta\, d\theta$) with (red-solid) and without (blue-dashed) accounting for the interaction with high-Z impurities. The terms $A(p,T)$ and $Z_b(p,T)$ are plotted in Fig. 2c (black and yellow curves, respectively), along with the standard friction term (green curve).

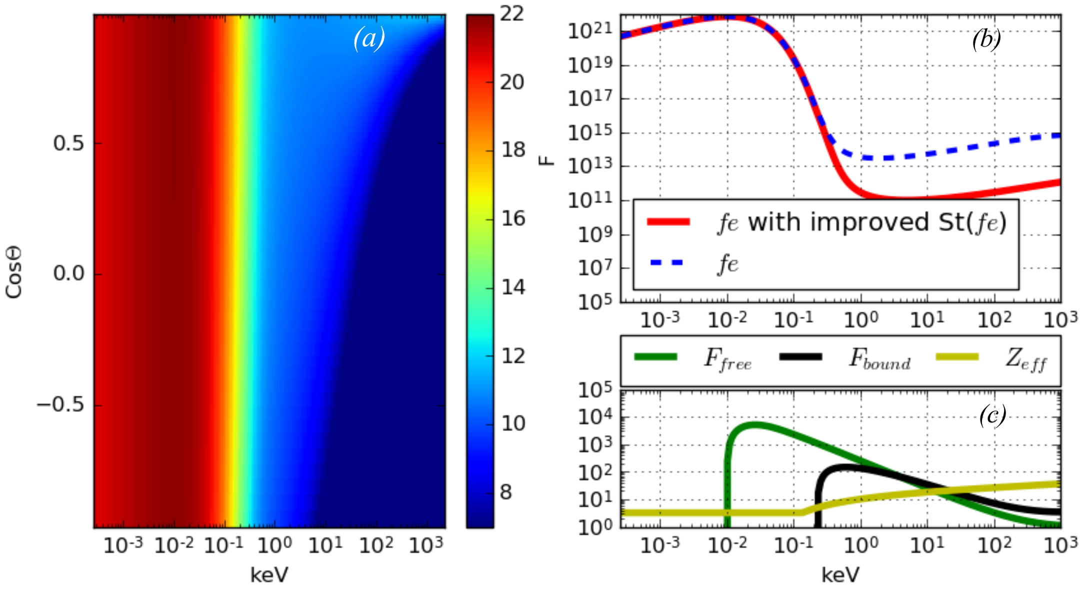


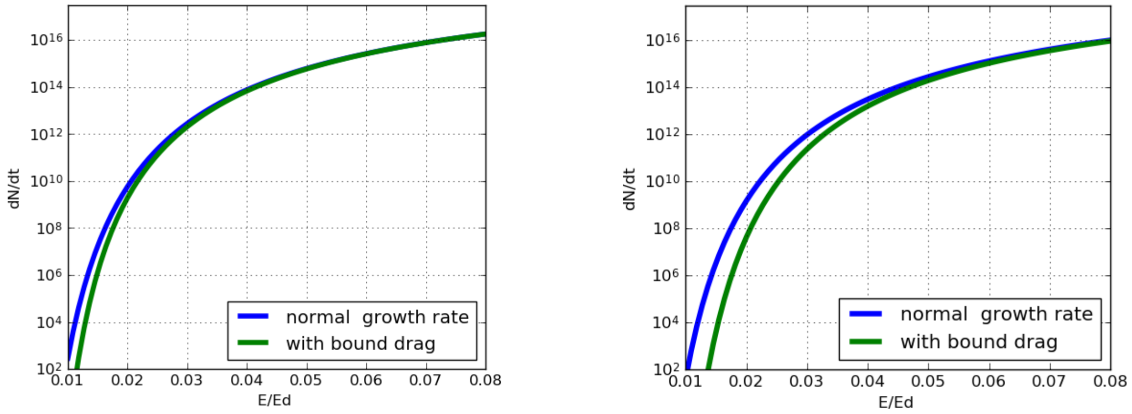
Figure 2. *(a) 2D Electron distribution function, (b) isotropic parts of the distributions $\int F \sin\theta \, d\theta$ with (red-solid) and without (blue-dashed) accounting for the interaction with High-Z impurities, (c) Stopping power (Green), A(p) (black) and Zb(p) (yellow) functions*

We conclude that the effect of the impurities becomes significant only for higher energy particles (~10 keV in the case of Fig. 2). Thus, electron distribution functions are similar in the thermal region, but the difference increases in the high-energy region, where the new terms are noticeable. We also note that the extra terms effectively "dumps" the distribution function thus hindering the RE production.

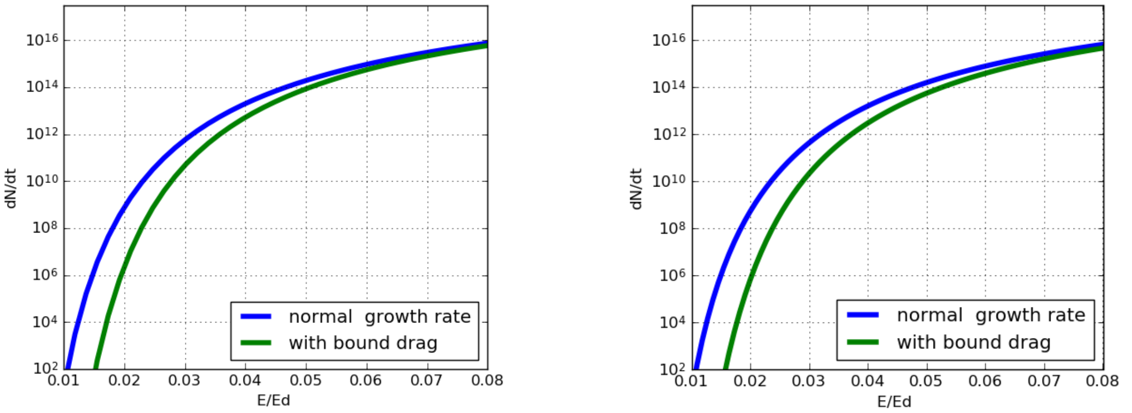
Figure 3 shows "Driecer flow" calculations for 4 different plasma temperatures, with (green curves) and without (blue curves) accounting for the interaction with high-Z impurities. The amount of Argon impurity was adjusted so that the free electron density is the same ($n_e=10^{20}m^{-3}$) in all cases. Hydrogen density is kept constant at $n_H=3\cdot10^{19}m^{-3}$

Increase of the electric field "shifts" the "Dreicer diffusion region" (a region of the distribution function where the deviation from Maxwellian becomes significant) toward the thermal energy region where the impact of the drag force on bound electrons is negligible. Therefore, we see in Fig. 3 that the rate of RE generation is less affected by the extra terms at high electric field. At the same time the difference between the flows is getting more noticeable for plasmas with higher temperatures. Remember that n_e is the same in all these cases, thus for each plot in Fig. 3 amount of impurity is adjusted. Finally we note that for plasma with the temperature 2 eV the impurity contribution is negligible for all electric fields.

In summary, our studies reviled the dumping effect of partially ionized impurities on Dreicer RE production (if compared with Dreicer flow as calculated with free electron density and classical Z_{eff}). The effect is smaller for higher electric fields.



(a) T= 2eV (b) T= 5eV



(c) T= 8eV (d) T= 10eV

Figure 3.*Dreicer rate dependence on electric field for 2eV (a), 5eV (b), 8eV (c), 10eV (d) plasmas with X,Y,Z,W argon density ($n_e=10^{20}m^{-3}$) with (green curves) and without (blue curves) accounting for integration with impurities.*

We are planning to do a larger parametric study to confirm the validity region of the analytical formula [3] and study if the formula can be updated to take the effect of impurities into account.

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