Runaway dynamics: sliding and screening

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We describe a theoretical framework for studying the effects of partial screening and collisional nonlinearities on runaway electron (RE) dynamics. We find significant enhancement of the collision frequencies due to partial screening, already at sub-relativistic electron energies. We show that Ohmic heating and the rate of heat loss play an important role in transition to slide-away.

Motivation

- Improved understanding of RE formation and decay processes are of prime interest for the safe operation of large tokamaks.

Kinetic modelling

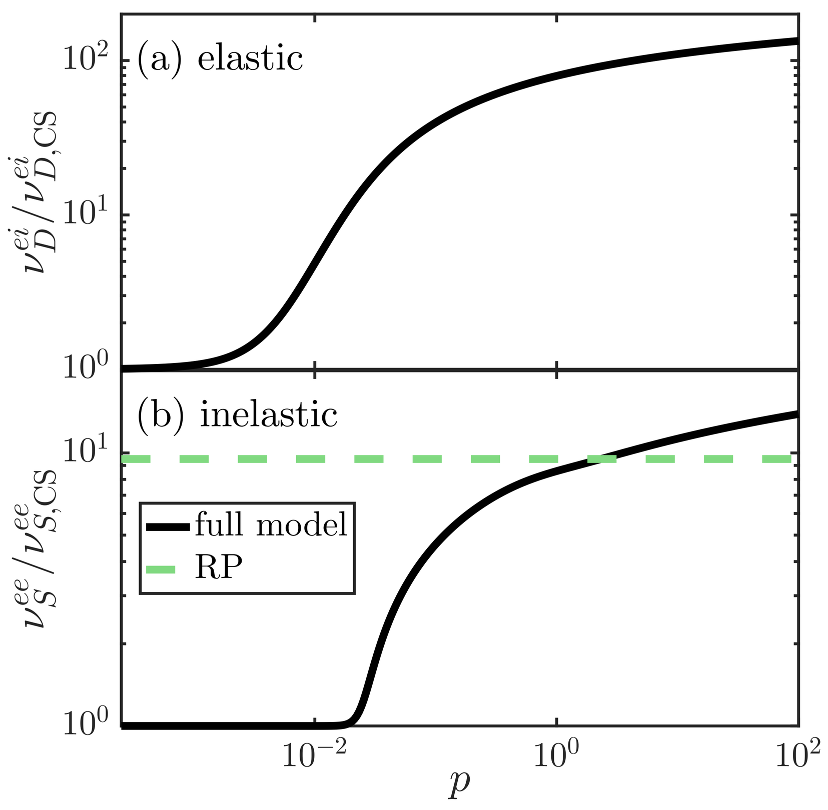
- CODE [1, 2] models acceleration in sub-Dreicer electric-fields, collisions, avalanche RE generation and radiation losses.
- NORSE [3] is a fully nonlinear relativistic tool, that can be used even when the runaway population becomes comparable to the thermal population or when the electric field is of the order of the Dreicer field.

Effect of partial screening [4, 5]

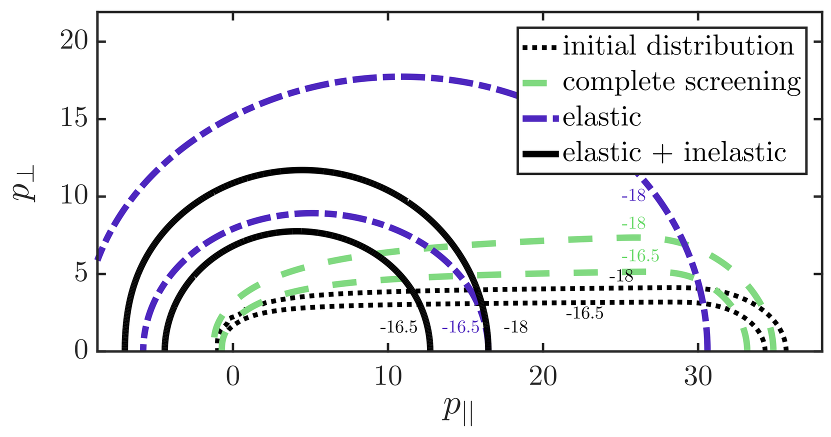
- Generalized collision operator including partial screening

$$C^e_{test} = \nu_D \mathcal{L}(f_e) + \frac{1}{p^2}\frac{\partial}{\partial p}\left[p^3\left(\nu_S f_e + \frac{1}{2}\nu_\parallel p \frac{\partial f_e}{\partial p}\right)\right]$$

- Model elastic collisions quantum-mechanically using density functional theory [5].
- Inelastic collisions: Bethe stopping power formula, mean-excitation energies from Ref. [6].
- Significant effect already at sub-relativistic energies.
- RP rule of thumb [7]: $\nu^{ee}_{S,\mathrm{RP}} \approx \nu^{ee}_{S,\mathrm{CS}}\left(1+\frac{1}{2}\sum_j \frac{n_j}{n_e} N_{e,j}\right)$



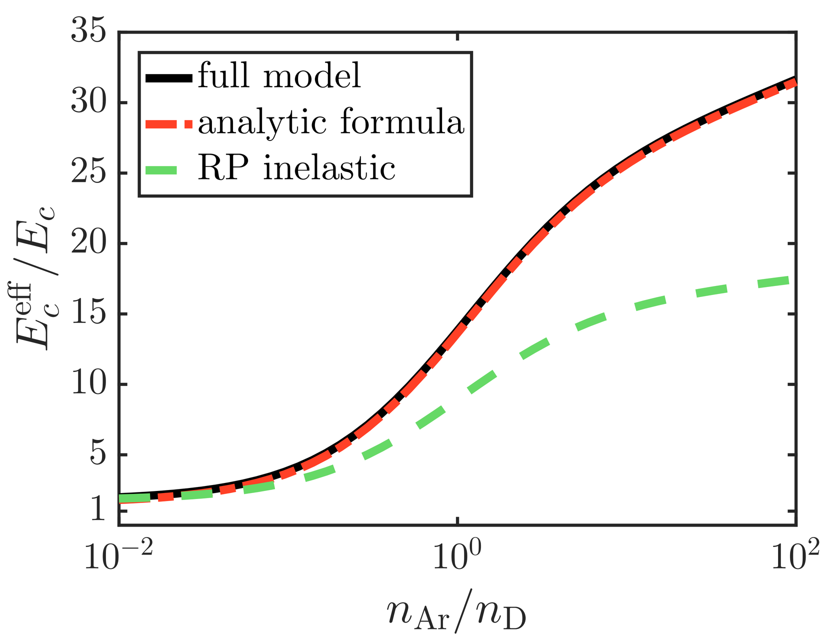
- 25 ms collisional deceleration of initial beam-like distribution
- Contours of $\log_{10}(F)$, $F=(2\pi m_e T)^{3/2} f_e/n_e$



$T = 10$ eV, $B = 4$ T, Ar$^+$, $n_{\mathrm{Ar}} = n_{\mathrm{D}} = 10^{20}$ m^{-3}.

Critical electric field

- Important for runaway growth and decay.
- Constant $\ln\Lambda$ and no screening or radiation effects: $E_c = \frac{n_e e^3 \ln\Lambda_0}{4\pi\epsilon_0^2 m_e c^2}$
- Significant effect from elastic collisions
- RP model underestimates E_c^{eff}



- Assume fast pitch-angle dynamics in Fokker–Planck equation [8]:

$$\frac{\partial \bar{f}}{\partial t} = \frac{\partial}{\partial p}\left[(p\nu_S - eE\xi)\bar{f}\right] + \frac{\partial}{\partial \xi}\left[(1-\xi^2)\underbrace{\left(\frac{eE}{pmc}\bar{f} + \frac{1}{2}\nu_D\frac{\partial \bar{f}}{\partial \xi}\right)}_{=0}\right]$$

where $\bar{f} = p^2 f$. Averaged force balance: $\langle eE_c^{\mathrm{eff}}\rangle = \min_p p\nu_S$.

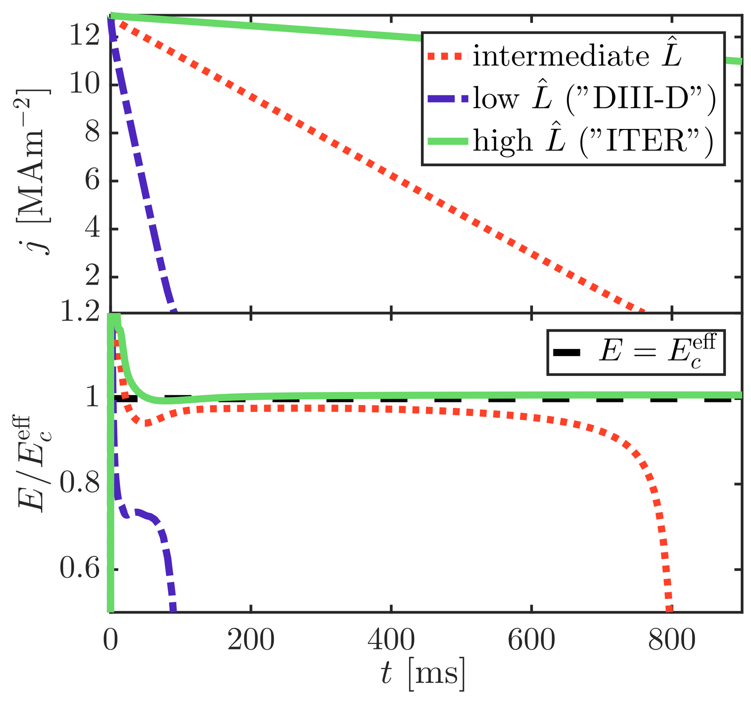
- Up to triply ionized argon $n_{\mathrm{Ar}} \gtrsim 0.1 n_{\mathrm{D}}$ (synchrotron neglected) [9]

$$\frac{E_c^{\mathrm{eff}}}{E_c} \approx 1 + \frac{1}{\ln\Lambda_0}\left(7 - \ln\sqrt{T_{\mathrm{eV}}} + 240\frac{n_{\mathrm{Ar,tot}}}{n_e}\right)$$

- Using Fokker–Planck solver CODE with 0-D inductive electric field

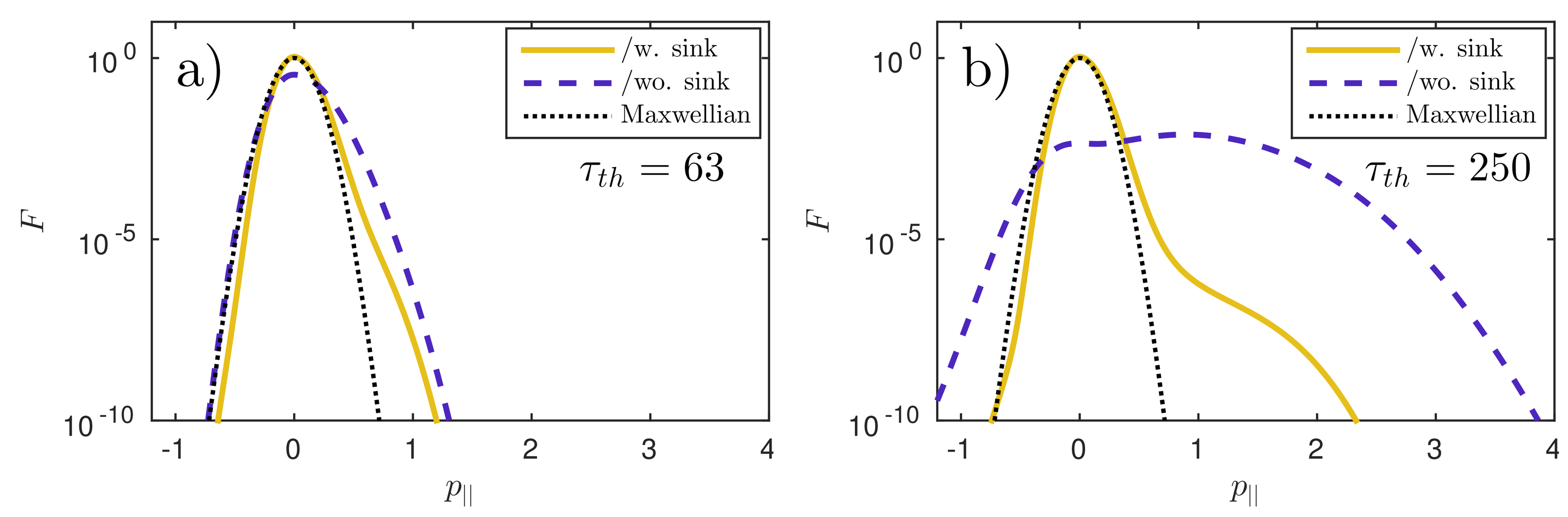
$$E = -\hat{L}\frac{\partial j}{\partial t}, \quad \hat{L} = \frac{AL}{2\pi R} \sim \frac{\mu_0 A}{2\pi}$$

- Forward-beamed initial distribution obtained by simulation with large E-field, average runaway energy: 17.2 MeV
- Test $-\hat{L}\frac{\partial j}{\partial t} = E \overset{?}{\approx} E_c^{\mathrm{eff}}$
- **Agreement at high inductance:** → current decay rate is $\propto E_c^{\mathrm{eff}}/\hat{L}$



Nonlinear effects

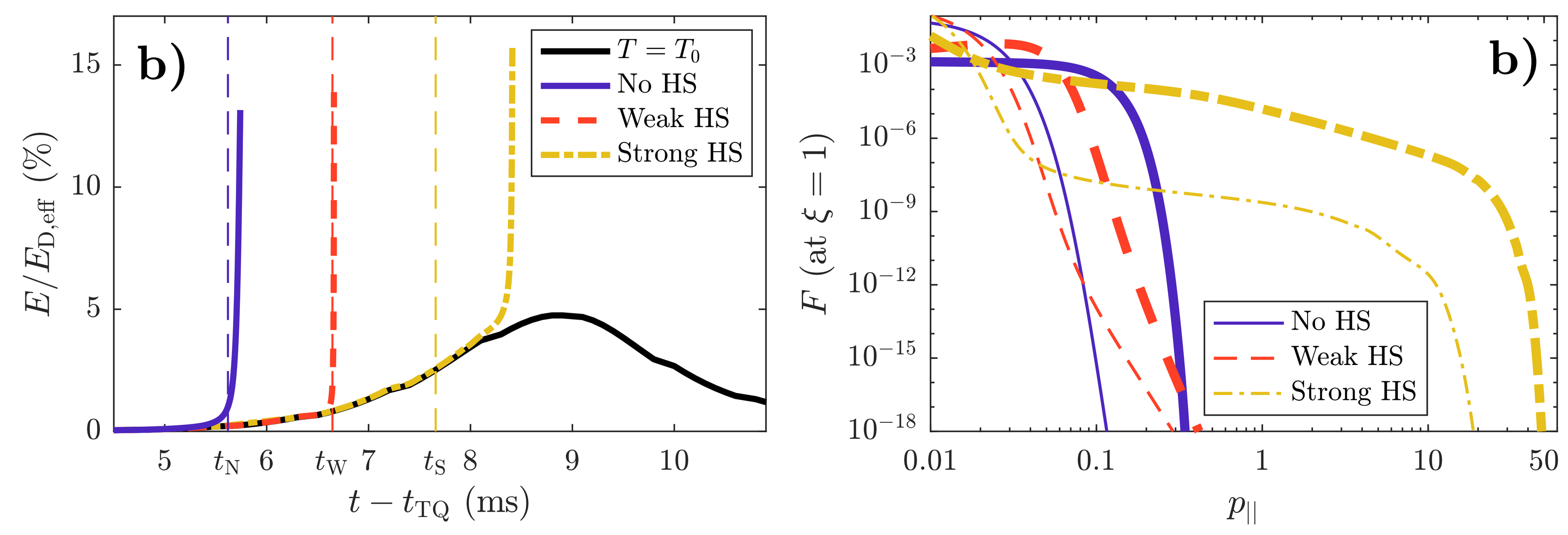
- Electric field heats up the electrons. Heating can induce a transition to the slide-away regime.



Distribution function in a NORSE run with a constant electric field of $E = 0.15$ V/m, $n_e = 5\cdot 10^{19}$ m^{-3}, $Z_{\mathrm{eff}} = 1$ and $B = 0$ T. At the initial temperature $T_e = 5.11$ keV, we have $E/E_{\mathrm{D}} = 0.035$ and $E/E_c = 3.5$.

ITER-like scenario with heat sink (HS) [10]

- E-field evolution calculated using linear tools [11]
- NORSE calculations show slide-away is reached early on in this scenario. Nonlinear treatment necessary to capture dynamics
- **No HS**: all energy supplied by the electric field remains; **Weak HS**: energy removal rate is restricted to 0.5 MW/m^3; **Strong HS**: keep bulk temperature at 10 eV.
- Energy reached by runaways depends strongly on time to slide-away transition (a few particles to high energy or many to low energy)



(Left) Effective normalized E-field strength (Right) Tail of the parallel electron distribution. Thin lines f at t_N (no HS), t_W (weak HS) and t_S (strong HS), and thick lines f immediately before the transition to slide-away.

Conclusions

- Enhancement of both collisional drag and pitch-angle scattering due to reduced screening lead to significant runaway electron decay.
- Analytical expressions for the effective critical electric field. Current decay rate $\propto E_c^{\mathrm{eff}}/\hat{L}$.
- Nonlinear collision operator: Important differences even when the electric field is much less than the Dreicer field.

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