Runaway electrons in fully-relativistic plasmas

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Runaway electrons due to toroidal electric field

Runaway electrons can be generated

- during the start-up phase of the discharge
- during the disruption.

Runaway electrons can be measured

- using synchrotron radiation —combined with hard X ray and neutron diagnostics. (Runaway electrons on EAST and HT-7 have been measured by these techniques.)

Runaways usually have energy $\sim \mathrm{MeV}$, and can

- cause severe damage to the vacuum if not well confined.
- carry a substantial amount of plasma current, thus may be beneficial to plasma confinement.

Collision friction and runaway problem

- The coulomb collision friction is usually a decreasing function in velocity for fast electrons, as shown in Fig. 1. If an electric field is applied to a plasma, a certain fraction of electrons will gain an energy such that the electric force on them exceeds the collision drag force and they will keep being accelerated. This process is called electron runaway

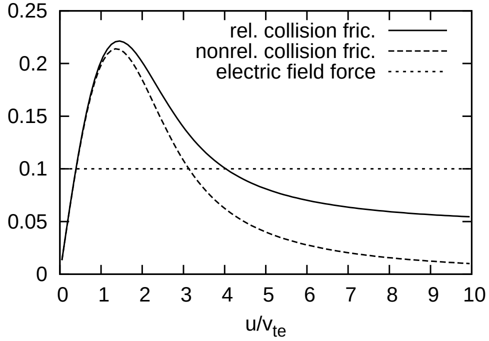

Figure 1. Electron-electron collision friction.

Relativistic Kinetic Equation

$$\frac{\partial f_e}{\partial t} + \boldsymbol{v} \cdot \nabla f_e + \frac{q_e}{m_e}\left(\boldsymbol{E} + \frac{\boldsymbol{v} \times \boldsymbol{B}}{c}\right) \cdot \nabla_u f_e = -\nabla_u \cdot \boldsymbol{S}_c, \tag{1}$$

where u is momentum-per-unit-rest-mass, m_e is rest-mass. Assuming f_e is spatial homogeneous and azimuthally symmetric about the magnetic field in velocity space. Then Eq. (1) reduces to

$$\frac{\partial f_e}{\partial t} = -\nabla_u \cdot (\boldsymbol{S}_c + \boldsymbol{S}_E),$$

where

$$\boldsymbol{S}_E = \frac{q_e \boldsymbol{E}}{m_e} f_e.$$

Diffusion and friction terms

Collision term can be written as

$$C(f_a, f_b) = -\nabla_u \cdot \boldsymbol{S}_c^{a/b},$$

where $\boldsymbol{S}_c^{a/b}$ is the collision flux, which can be written in the Fokker-Planck form

$$\boldsymbol{S}_c^{a/b}(\boldsymbol{v}) = -\boldsymbol{D}_c^{a/b} \cdot \nabla_u f_a(\boldsymbol{v}) + \boldsymbol{F}_c^{a/b} f_a(\boldsymbol{v}),$$

where $\boldsymbol{D}_c^{a/b}$ is the diffusion tensor, and $\boldsymbol{F}_c^{a/b}$ is the friction vector. Flux due to electric field is given by

$$\boldsymbol{S}_E = \frac{q_e \boldsymbol{E}}{m_e} f_a,$$

which has only friction term.

Electron collision

$$C_e(f_e) = C(f_e, f_e) + C(f_e, f_i),$$

where the electron-ion collision term is accurately modeled by the pitch angle scattering operator

$$C(f_e, f_i) = \Gamma^{e/e} \frac{Z_i}{2vu^2} \frac{1}{\sin\theta} \frac{\partial}{\partial\theta}\left(\sin\theta \frac{\partial f_e}{\partial\theta}\right).$$

We use linearized operator to model electron-electron collision

$$\begin{aligned} C(f_e, f_e) &\approx C(f_{e1}, f_{em}) + C(f_{em}, f_{e1}) \\ &= C(f_e, f_{em}) + C(f_{em}, f_e) \\ &\equiv C^l(f_e) \end{aligned}$$

$$C^l(f_e) \approx C(f_e, f_{em}) \equiv C_{\max}(f_e)$$

Numerical grids and definition of runaway rate

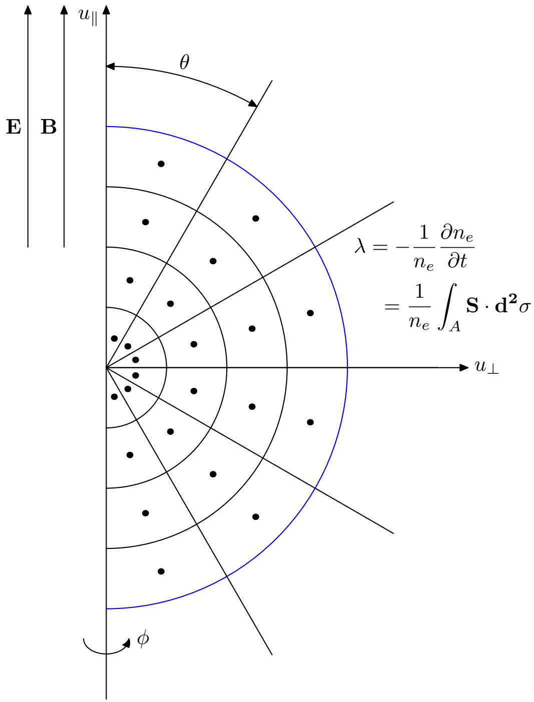

Figure 2. Numerical grids and the definition of runaway rate.

Benchmark of the 2D Fokker-Planck code

- Conductivity agrees well with Spizter conductivity
- The results of Lower-hybrid current drive agrees well with Karney’s

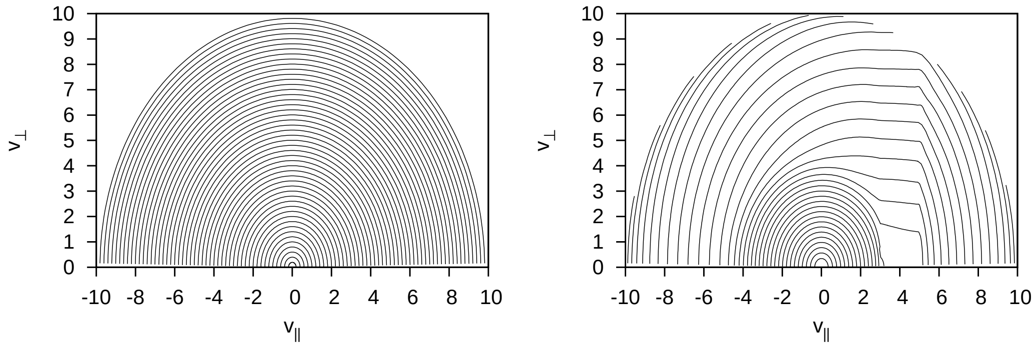

Figure 3. Contour of the initial Maxwellian distribution and the final steady-state distribution due to Lower-hybrid wave diffusion.

Runaway steady-state distribution

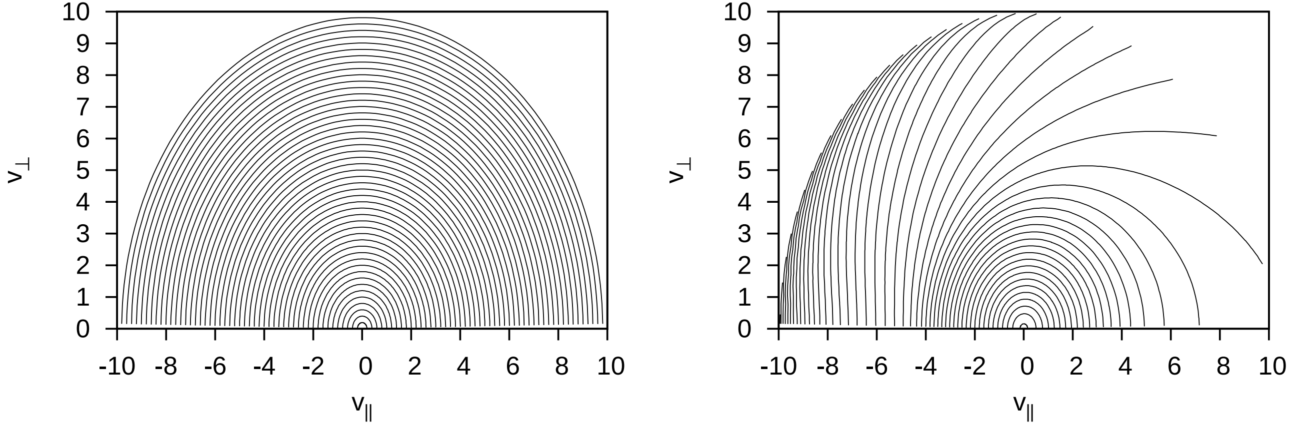

Figure 4. Contour of the initial Maxwellian distribution and the final steady-state distribution in the presence of a dc electric field.

Runaway rate

Analytical theory gives

$$\lambda = K(Z_i)\left(\frac{E}{E_0}\right)^{-3(Z_i+1)/16} \exp\left(-\frac{1}{4E/E_0} - \sqrt{\frac{Z_i+1}{E/E_0}}\right),$$

where $K(Z_i)$ is a function of Z_i.

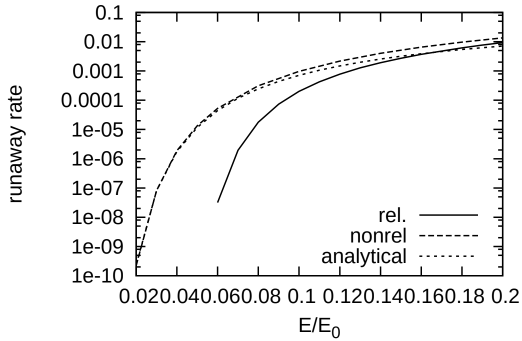

Figure 5. Runaway rate as a function of E/E_0

Runaway calculated by MC collision operator

$$C^l(f_e) = C(f_e, f_{e\,m}) + C(f_{e\,m}, f_e)$$
$$\approx C(f_e, f_m) + C(f_m, f_{e1}P_1(\cos\theta))$$

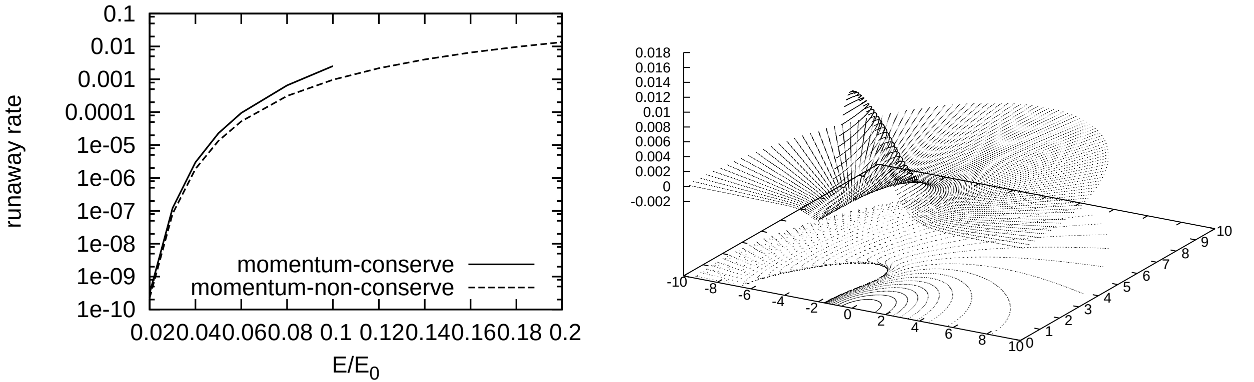

Figure 6. Runaway distribution function calculated by momentum conserving collision operator

Summary

- We have developed a 2D relativistic Fokker-Planck code which can calculate Lower-hybrid current drive efficiency and electron runaway rate.
- Electron runaway rate is reduced when relativistic effects are considered.
- For relativistic plasma, there is an threshold below which runaway is impossible.
- We tried to improve the collision operator used in the runaway calculation by retaining the momentum-conserving term of the electron-electron collision.
- The runaway rate predicted by the momentum-conserving collision operator is larger than that by the Maxwellian operator used in the analytical theory
- However, for the improved collision operator, the distribution function may become negative when the electric field is large.

Thanks!