Effects of the synchrotron radiation and pitch angle scattering on the secondary runaway electron growth

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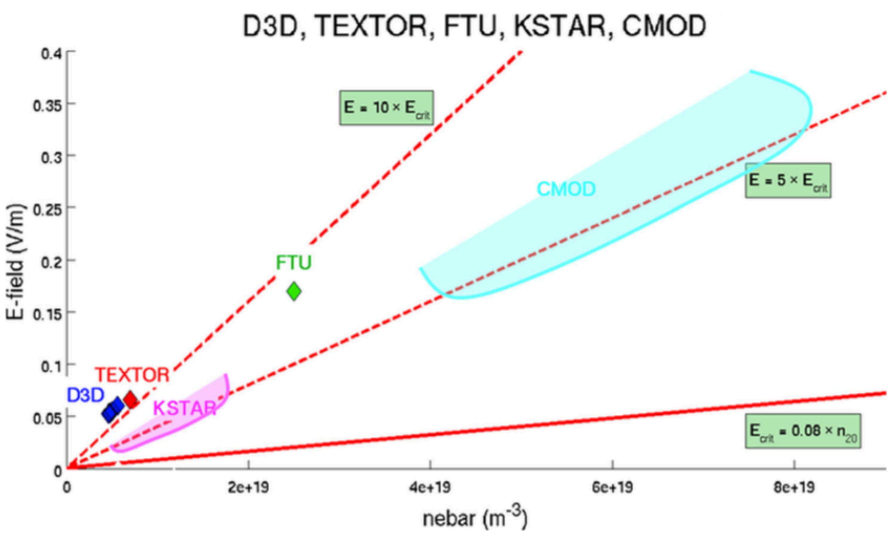
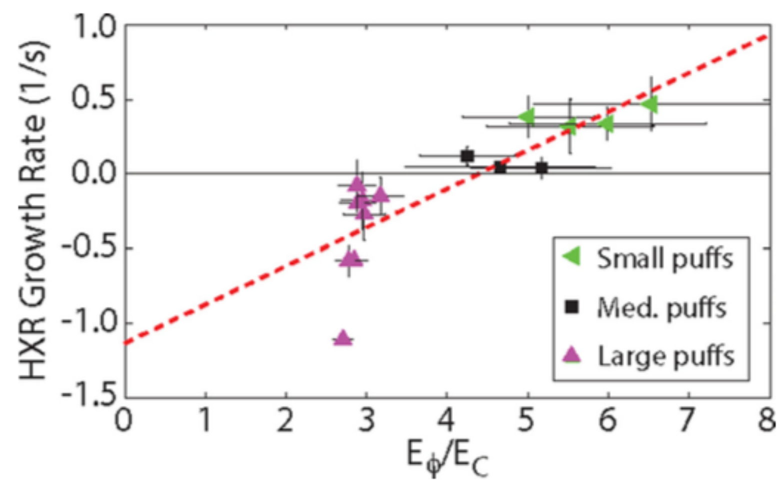
Motivation

- In recent runaway experiments, critical electric field which is several times larger than the Connor-Hastie E_c are observed for the runaway growth.





- The discrepancy may be due to the finite sensitivities of the detectors.
- It is also possible that there are some new energy loss mechanisms, which can be important to ITER runaway electron mitigation.

R.S. Granetz et al., Phys. Plasmas **21**, 072506 (2014).
C. Paz-Soldan et al., Physics of Plasmas (1994-Present) **21**, 022514 (2014).

Synchrotron radiation back reaction force

- For high energy runaway electrons, the energy loss from the synchrotron radiation can be important and comparable to the *E* field and collisional drag. This effect can be described by the radiation reaction force:

$$\mathbf{F}_S = \frac{2}{3} r_e m_e c^2 \beta^2 \gamma \left\{ \frac{\sin^2\theta}{r_g{}^2} \left[(1 + p_\perp{}^2)\mathbf{p}_\perp + p_\perp^2 p_\parallel \hat{b} \right] + \frac{\beta\gamma^3}{R_0^2} \hat{b} \right\}$$

- For runaway electron with γ<100, the contribution from the magnetic field curvature is much smaller than the Larmor motion.

I. B. Bernstein and D. C. Baxter, Phys. Fluids **24**, 108 1981.

Secondary runaway generation

- The kinetic equation for runaway electron can be written as

$$\frac{\partial f}{\partial t} - eE\hat{b}\cdot\nabla_p f - C\{f\} + \nabla_p \cdot (\mathbf{F}_S f) = S$$

- In the paper by Rosenbluth and Putvinski, the secondary runaway electron generation is described as a source term in the kinetic equation:

$$S = \frac{n_r}{\tau \ln\Lambda}\delta(\xi - \xi_2)\frac{1}{p^2}\frac{\partial}{\partial p}\left(\frac{1}{1-\sqrt{1+p^2}}\right), \quad \xi_2 = \frac{p}{1+\sqrt{1+p^2}}$$

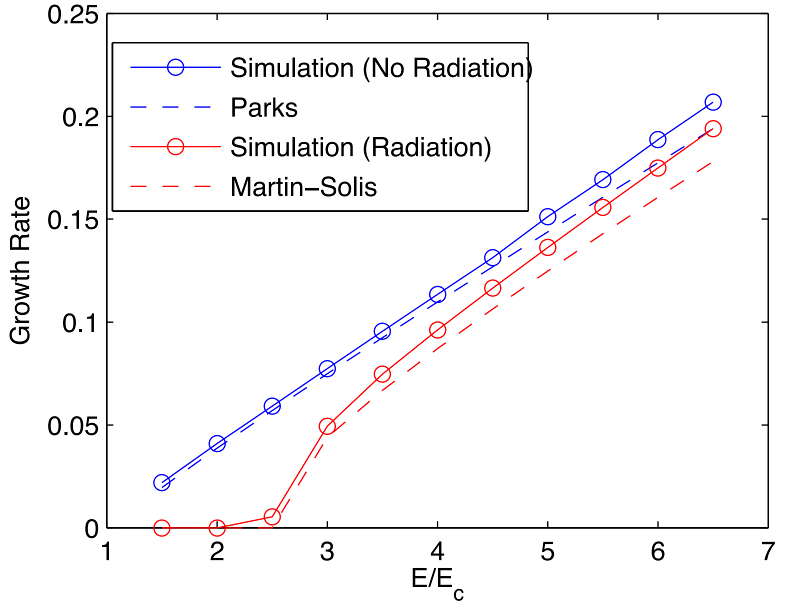
- The growth rate is given by integrate S in the phase space. However, one need to determine the critical runaway electron energy γ_{c} (runaway boundary in phase space) in order to give the integral boundary.

Simulation method

- In this work, we use the simulation method developed by M. Landreman. We solve the kinetic equation in a time-dependent approach.
- We added the synchrotron radiation back-reaction force into the kinetic equation.
- The distribution function f is calculated using finite-difference in p and Legendre polynomials spectrum in ξ.
- We wait long enough until the growth rate of runaway electrons becomes a constant.

M. Landreman, A. Stahl, and T. Fülöp, Comp. Phys. Comm. **185**, 847 (2014).

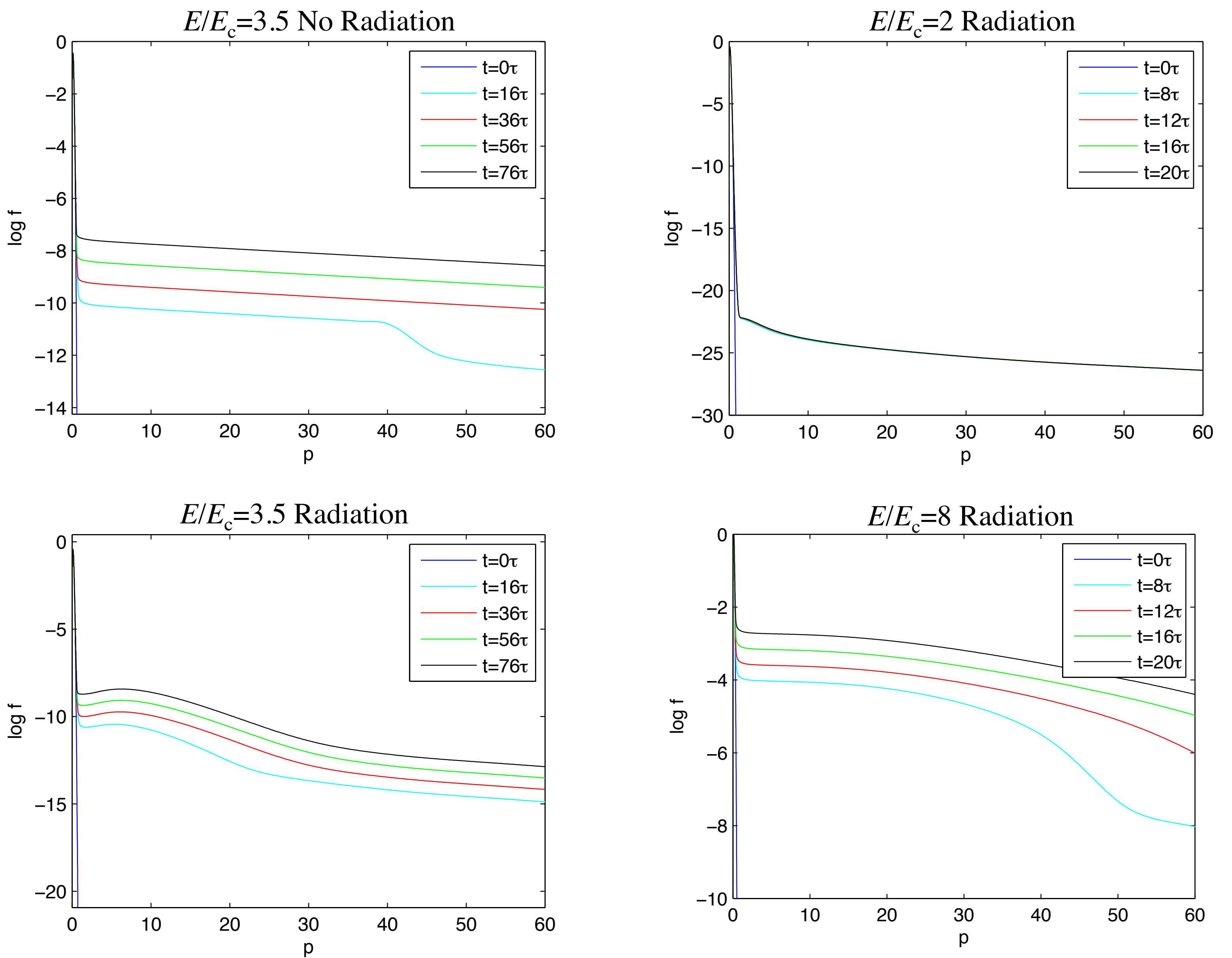
Avalanche growth rate for Z=1



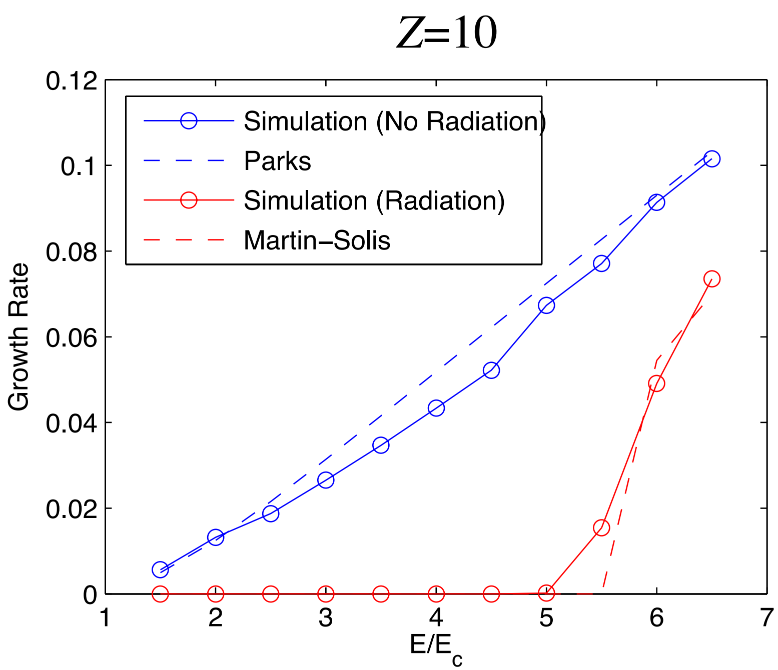
Growth rate is normalized to $\tau_e = \dfrac{4\pi\epsilon_0^2 m_e^2 c^3}{n_e e^4}$

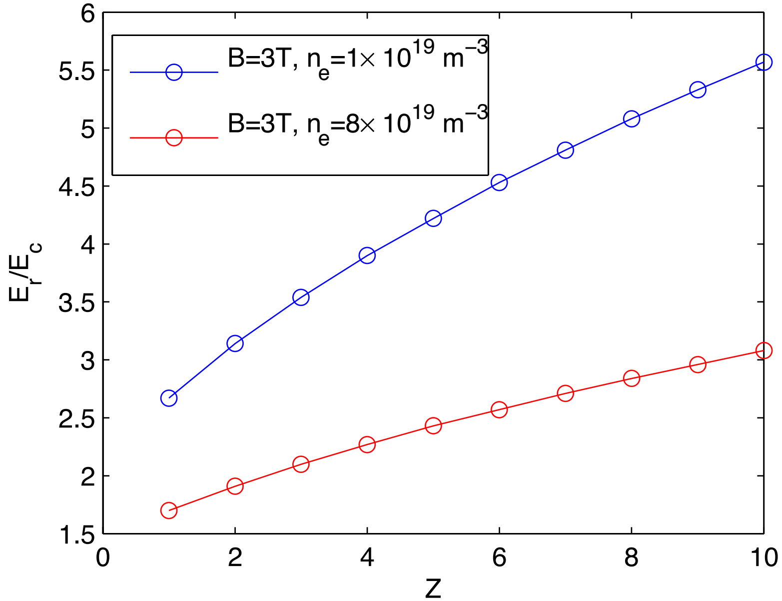
- In the no radiation case, the growth rate is almost a linear function of E/E_c.
- In the radiation case, there is a new threshold $E_r > E_c$, below which the growth rate is zero. For large E the difference is small.
- Simulation and theory are pretty close. The discrepancy is larger for large E.

Distribution function



Avalanche growth rate for high *Z*



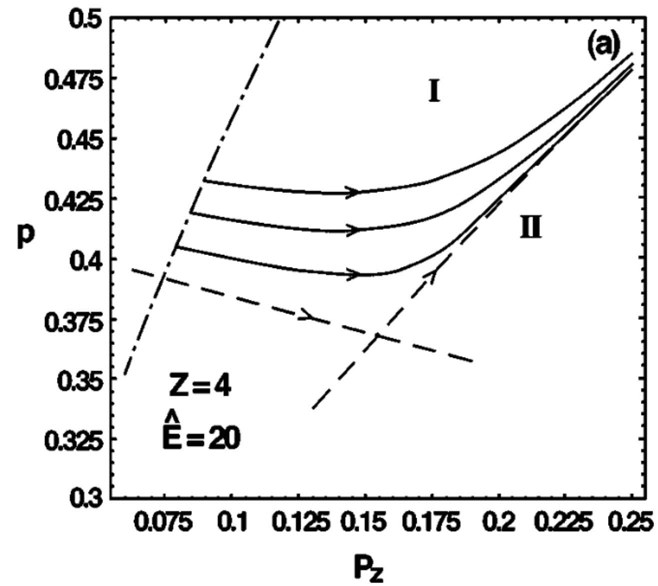


- In no radiation case, large *Z* does not change the threshold value.
- The threshold E_r depends on *Z*.

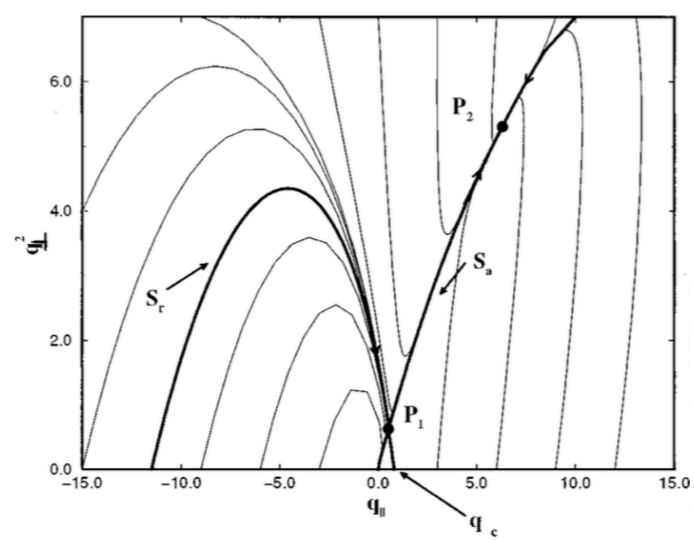
Test particle model

- Following Rosenbluth-Putvinski paper, P. Parks developed a test particle method to determine the runaway boundary and avalanche growth rate by ignoring the second-order term in the pitch angle scattering operator.

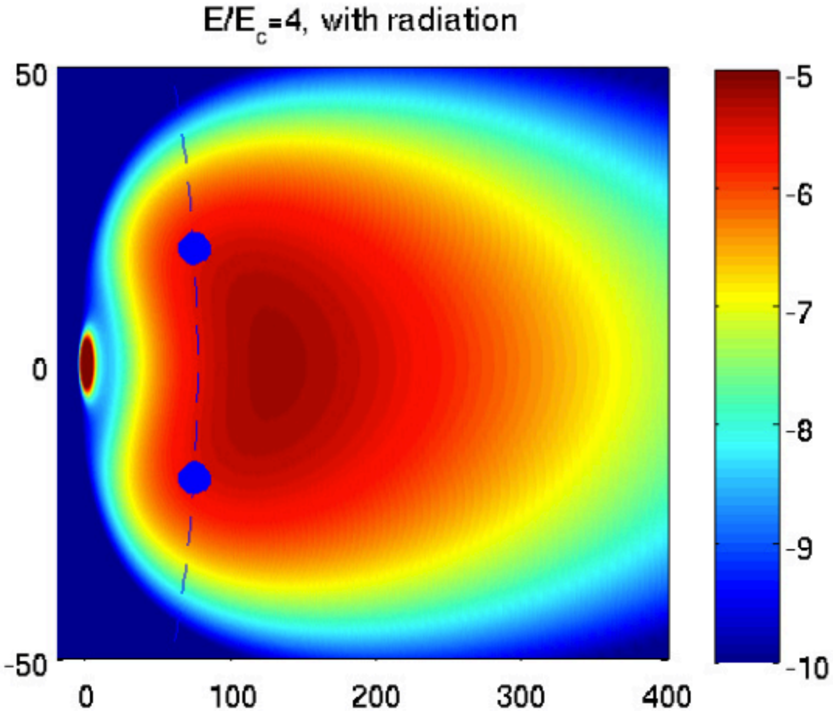
$$\frac{1}{2}\frac{\partial}{\partial\xi}(1-\xi^2)\frac{\partial f}{\partial\xi} = \frac{\partial}{\partial\xi}(\xi f) + \boxed{\frac{\partial^2}{\partial\xi^2}\left(\frac{1-\xi^2}{2}f\right)}$$

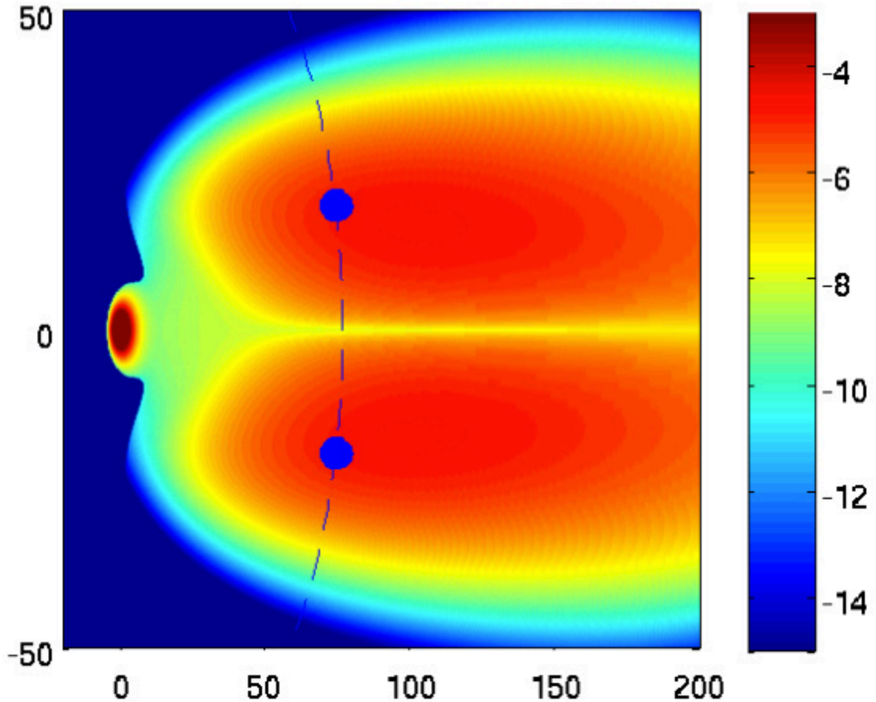


- Martin-Solis et al. extended Parks' test particle model to study the phase space structure of runaway electrons with the radiation effect. A new attractor is found in the phase space. They also found changes of the threshold and growth rate of secondary runaway electron.



P.B. Parks, M.N. Rosenbluth, and S.V. Putvinski, Physics of Plasmas (1994-Present) **6**, 2523 (1999).
J.R. Martı´n-Solı´s, R. Sánchez, and B. Esposito, Physics of Plasmas (1994-Present) **7**, 3814 (2000).





$$C_Z(f) = \frac{\partial}{\partial \xi}\left(\xi f\right) + \frac{\partial^2}{\partial \xi^2}\left(\frac{1-\xi^2}{2} f\right)$$

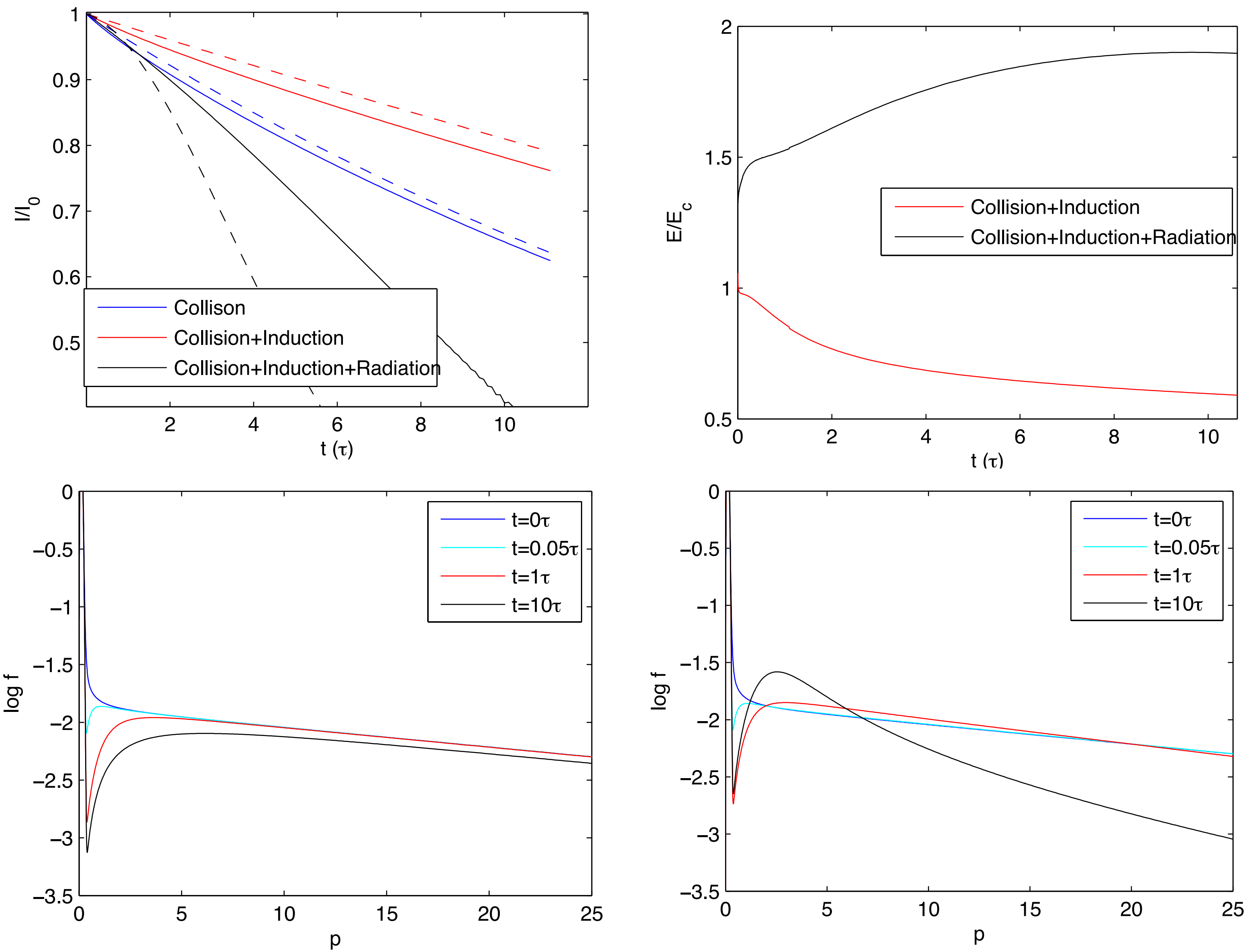
$$C_Z(f) = \frac{\partial}{\partial \xi}\left(\xi f\right) + \frac{1}{2}\frac{\partial^2}{\partial \xi^2}\left(\frac{1-\xi^2}{2} f\right)$$

Post-disruption runaway decay

- After the thermal quench, the plasma current has been transformed to runaway current.
- In the thermal quench $E/E_c \gg 1$, runaway electrons are mainly formed by secondary generation. The average energy of runaway electron is about $2\ln\Lambda$.
- Three effects are important in the RE current decay process, the collisional drag, the induction electric field $E=-LdI/dt$, and the radiation loss.

$$\frac{I(t)}{I_0}\exp\left[\frac{l}{2\ln\Lambda\, I_A}(I(t)-I_0)\right]=\mathrm{sech}\left(t\sqrt{\frac{1+Z}{\tau\tau_r\ln\Lambda}}\right)\exp\left(-\frac{t}{2\tau\ln\Lambda}\right)$$

F. Andersson, P. Helander, and L.-G. Eriksson, Phys. Plasmas **8**, 5221 (2001).



I/I0
t (τ)
Collison
Collision+Induction
Collision+Induction+Radiation
E/Ec
t (τ)
Collision+Induction
Collision+Induction+Radiation
log f
p
t=0τ
t=0.05τ
t=1τ
t=10τ
log f
p
t=0τ
t=0.05τ
t=1τ
t=10τ

Conclusion

- For the secondary runaway generation (avalanche) process, we found a new critical electric field $E_r > E_c$ due to the synchrotron radiation effect.
  - For $E < E_r$, there is no avalanche process. f is monotonically decay and will stagnate.
  - For $E > E_r$ but not too large, the secondary runaway growth rate is less than the non-radiation case. f will have a bump-on-tail due to the radiation force.
  - For $E \gg E_r$, the growth rate is close to the non-radiation result. f is again a monotonically decaying function.

- E_r is a combined effect of synchrotron radiation and pitch angle scattering. Other effects including magnetic perturbation and whistler wave scattering are also expected to change E_r.

- Synchrotron radiation effect is very important to post-disruption runaway current decay. It will change the shape of runaway electron beam distribution function.

Next steps

- We are now working on an experimental proposal on DIII-D to study the critical electric field under high-Z condition and the runaway energy distribution (bump-on-tail?). We will conduct a synthetic diagnostic simulation for the flat-top case and compare the results with the experiments.

- Calculate a more precise source term in the kinetic equation by dropping the assumptions that all runaway electrons are highly energetic. This can allow us to study a complete process of runaway growth, including a transition from Dreicer to avalanche.

- Study other loss mechanisms, including the magnetic field fluctuation and the whistler wave scattering.

- Couple to kinetic simulation to MHD code.

$$\frac{t_{\text{fric}}}{t_{\text{rad}}} = 1.6 B_T \sqrt{\frac{1+Z}{n_{19}}}$$