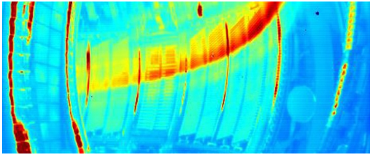
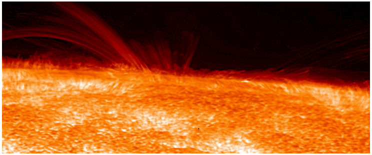
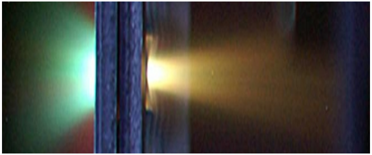
Running away and radiating

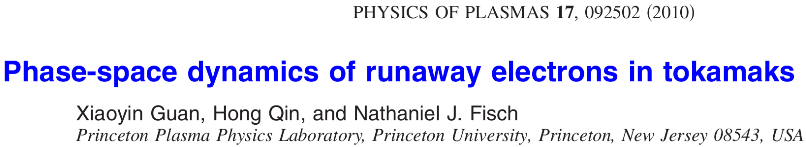


Runaway electrons in fusion plasmas





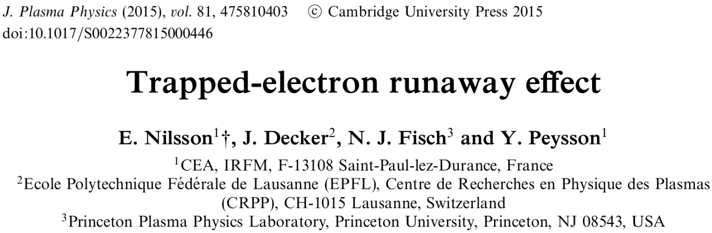
Tünde Fülöp, Department of Physics
Chalmers University of Technology, Sweden



PHYSICS OF PLASMAS **17**, 092502 (2010)

Phase-space dynamics of runaway electrons in tokamaks

Xiaoyin Guan, Hong Qin, and Nathaniel J. Fisch
Princeton Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08543, USA



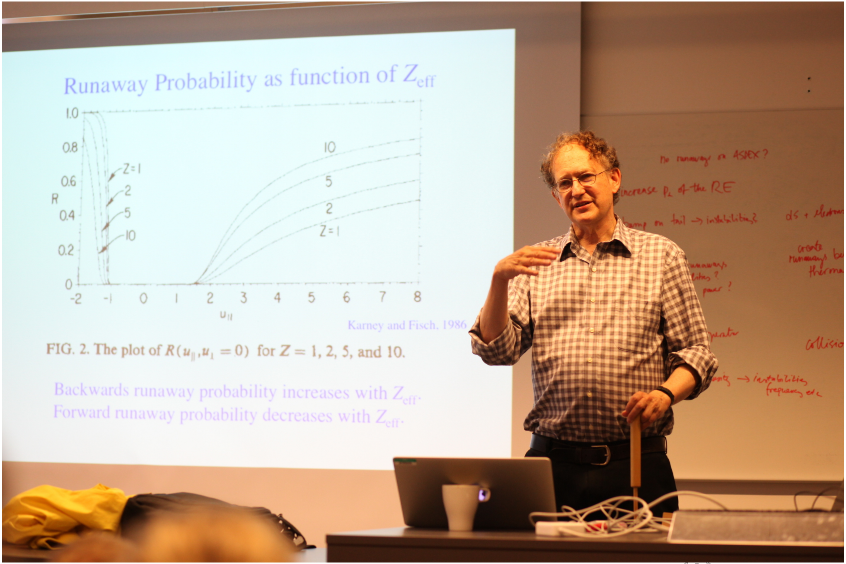
J. Plasma Physics (2015), *vol.* 81, 475810403 © Cambridge University Press 2015
doi:10.1017/S0022377815000446

Trapped-electron runaway effect

E. Nilsson[1]†, J. Decker[2], N. J. Fisch[3] and Y. Peysson[1]

[1]CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France
[2]Ecole Polytechnique Fédérale de Lausanne (EPFL), Centre de Recherches en Physique des Plasmas (CRPP), CH-1015 Lausanne, Switzerland
[3]Princeton Plasma Physics Laboratory, Princeton University, Princeton, NJ 08543, USA

Runaway electron modelling workshop at Chalmers



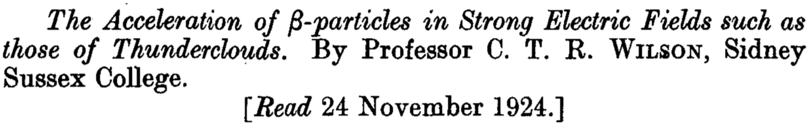
Runaway Probability as function of $Z_{\rm eff}$

Karney and Fisch, 1986

FIG. 2. The plot of $R(u_\parallel, u_\perp = 0)$ for $Z = 1, 2, 5$, and 10.

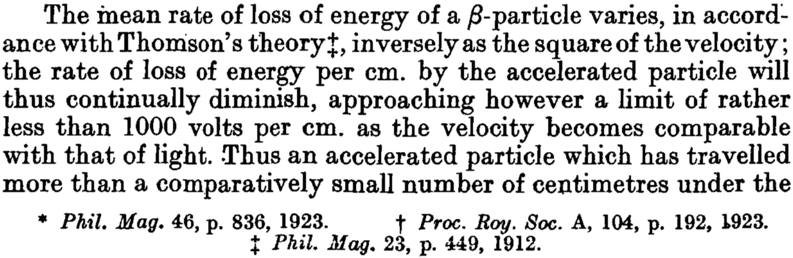
Backwards runaway probability increases with $Z_{\rm eff}$.
Forward runaway probability decreases with $Z_{\rm eff}$.

CTR Wilson 1924



The Acceleration of β-particles in Strong Electric Fields such as those of Thunderclouds. By Professor C. T. R. Wilson, Sidney Sussex College.

[*Read* 24 November 1924.]



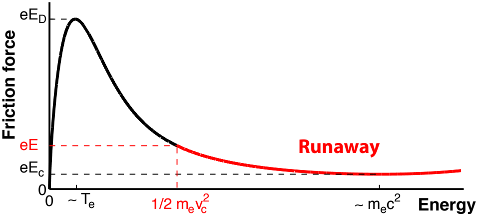
The mean rate of loss of energy of a β-particle varies, in accordance with Thomson's theory[‡], inversely as the square of the velocity; the rate of loss of energy per cm. by the accelerated particle will thus continually diminish, approaching however a limit of rather less than 1000 volts per cm. as the velocity becomes comparable with that of light. Thus an accelerated particle which has travelled more than a comparatively small number of centimetres under the

[*] *Phil. Mag.* 46, p. 836, 1923.

[†] *Proc. Roy. Soc.* A, 104, p. 192, 1923.

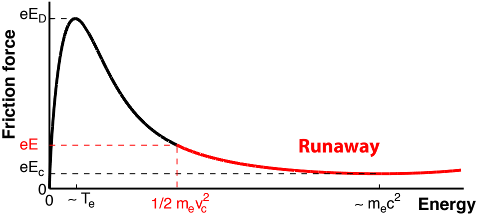
[‡] *Phil. Mag.* 23, p. 449, 1912.

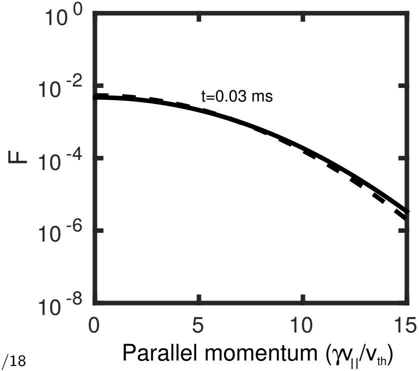
Runaways in plasmas



- Runaway acceleration of some electrons if $E > E_c$ $E_c(\mathrm{V/m}) \simeq n_e(10^{21}\ \mathrm{m}^{-3})$ (Dreicer generation)

Runaways in plasmas





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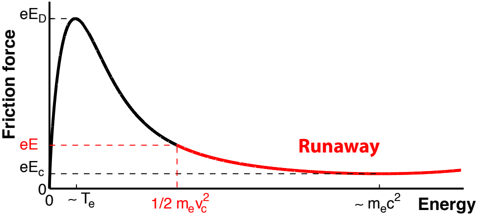

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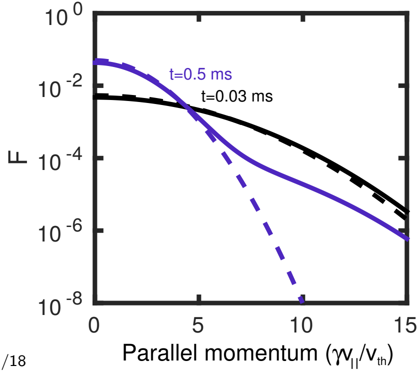
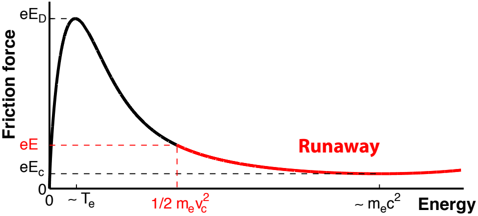


Hot-tail generation

- In case of sudden cooling an elevated tail of the distribution can run away.
- Dominates if the timescale is shorter than the collision time at the critical velocity

Runaways in plasmas



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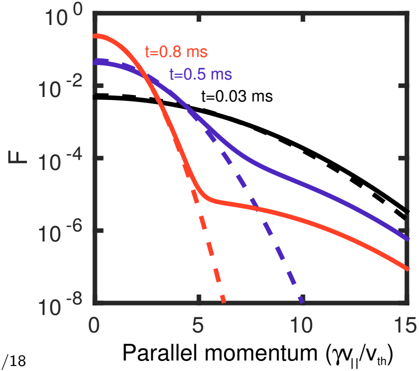

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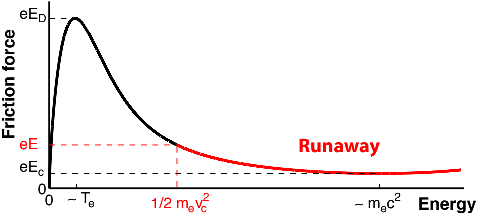
Runaways in plasmas



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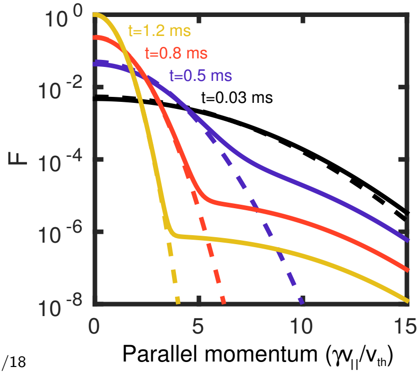

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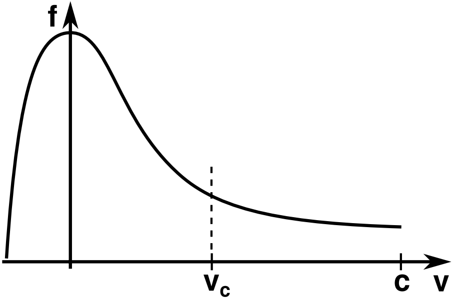
Knock-on/avalanche generation of runaways

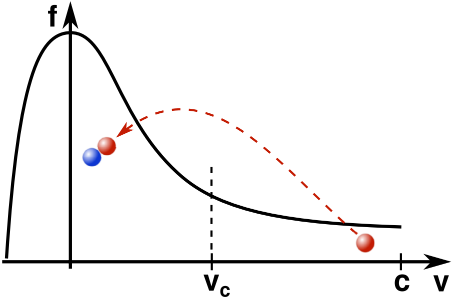
Large-angle collisions



- In a close Coulomb collision an existing runaway electron can throw a thermal electron above the runaway threshold.

Knock-on/avalanche generation of runaways

Large-angle collisions



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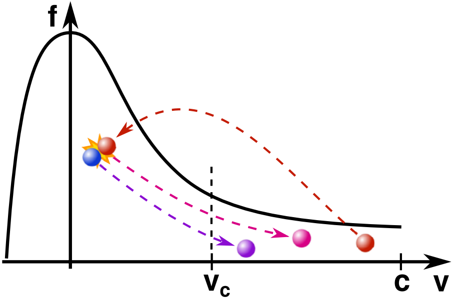

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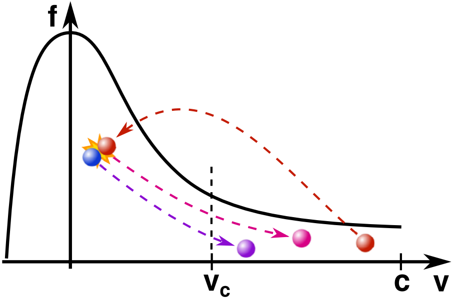


- In a close Coulomb collision an existing runaway electron can throw a thermal electron above the runaway threshold.

- Exponential growth of runaways! Growth rate

$$\gamma_{RA} = \frac{1}{j_{RA}}\frac{dj_{RA}}{dt} \simeq \frac{eE}{2m_e c \ln\Lambda}$$

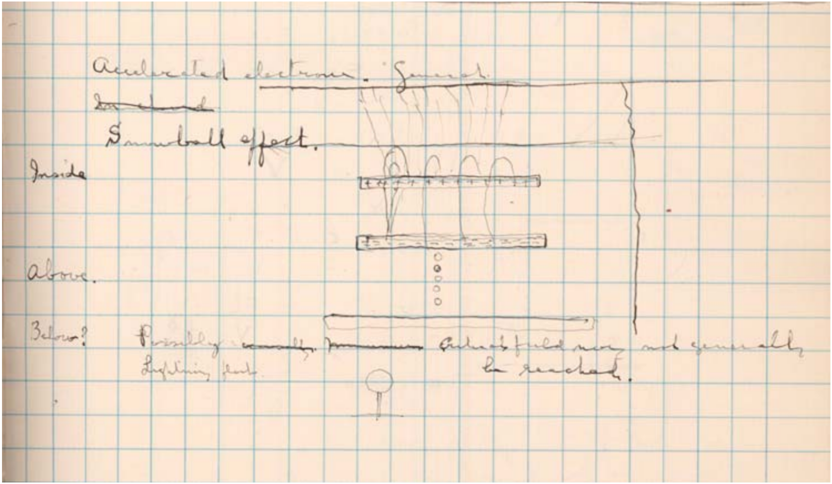
- Total number of e-folds during an avalanche

$$\gamma_{RA} t \simeq \frac{eEt}{2m_e c \ln\Lambda} \simeq \frac{I_p}{I_A \ln\Lambda}$$

where $I_A = 0.017\,\mathrm{MA}$.

- Avalanche multiplication in ITER $\sim e^{50}$

Snowball effect (CTR Wilson's notebook)



Accelerated electrons. General.

~~In cloud~~

Snowball effect.

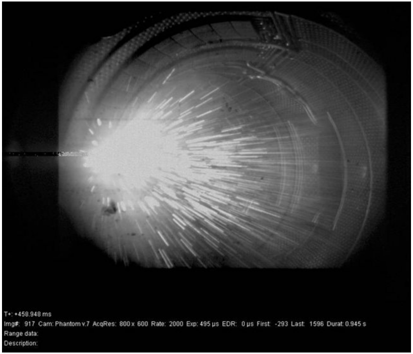
Inside

Above.

Below? Possibly ~~usually~~ ~~[illegible]~~ critical field may not generally
Lightning flash
be reached.

Runaways in disruptions

- In tokamak disruptions:
    - the plasma cools quickly,
    - the resistivity $\eta \propto T^{-3/2}$ rises, and
    - a high electric field is induced to maintain the plasma current.
- The pre-disruption current is partly replaced by a current of runaway electrons:
    - electrons are accelerated to tens of MeV,
    - usually hit the wall → hard X-rays,
    - can cause substantial damage.



Carbon dust particles produced when runaways hit a plasma-facing component in Tore Supra.

Damaging potential is huge

"Several kg of molten material can be produced (and can be moved around by gravity and **j** × **B** forces) by a single runaway event." [Progress in ITER Physics Basis, NF **47** S180 (2007)]

Mitigation

- What are the destructive effects and how can these be mitigated?

Control

- Can we control the runaway beam formation?

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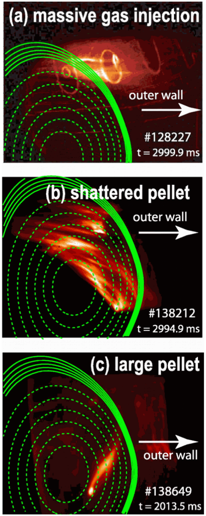
Control and/or mitigation

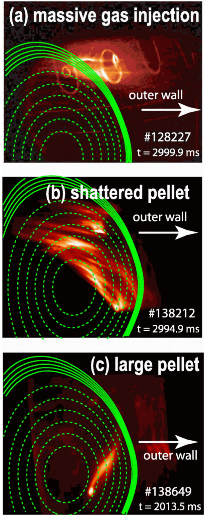
- Runaways can be suppressed by
  - increased collisional suppression
    - massive gas injection
    - shattered pellet injection
    - solid pellet injection



[Hollmann et al, PP (2015)]

Control and/or mitigation

- Runaways can be suppressed by
  - increased collisional suppression
    - massive gas injection
    - shattered pellet injection
    - solid pellet injection
  - enhancement of losses via magnetic perturbations
    - $\delta B/B \sim 0.1\%$ required



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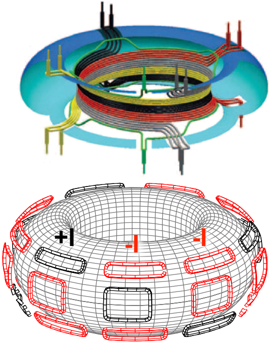

[Papp et al, JPP (2015); PPCF (2012) & (2011); NF (2011)]

Radiation reaction forces

Synchrotron:

- Emitted by runaways due to gyromotion, $P_{\text{tot}} \propto p_{\perp}^{2}$

Bremsstrahlung:

- Emitted in inelastic collision between runaways and bulk particles

Radiation reaction forces

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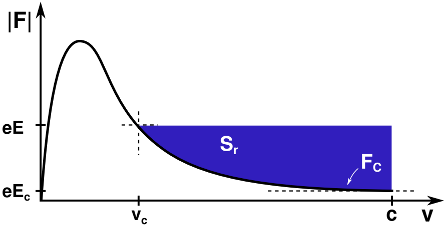
Radiation emission is associated with a reaction force



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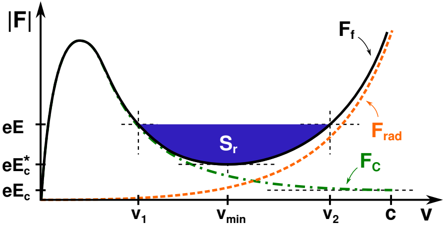
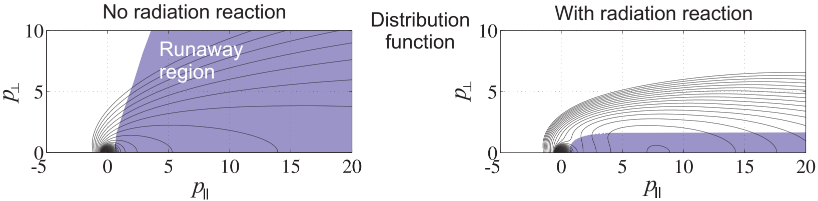


- Critical field for runaway is now E_c^* ($> E_c$)

[Stahl et al, PRL (2015)]

Effect of synchrotron radiation reaction

- Runaway region shrinks to a region of small perpendicular momenta.
- Bump on tail formation may be observed.
- Bump location $\propto$ typical runaway energy.



[Hirvijoki et al, JPP (2015), Decker et al, PPCF (2016)]

Improved modelling of bremsstrahlung losses

Previously, bremsstrahlung losses were studied using an effective friction force.

- Improved bremsstrahlung model accounting for finite photon energy, derived from the Boltzmann collision operator.
- A significant fraction of runaway electrons reach at least twice the energy allowed in the "mean-force" model.

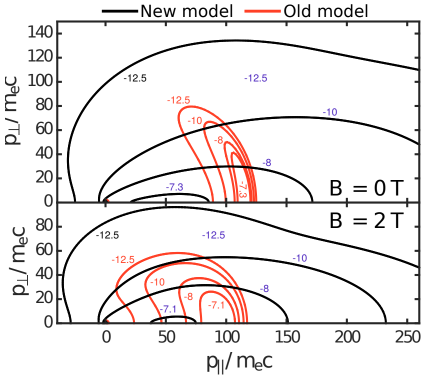


Figure : Runaway-electron distribution for $E/E_c = 2$, $Z_{\text{eff}} = 10$ and $n_e = 3 \cdot 10^{21}\ \text{m}^{-3}$. With (lower) and without (upper) synchrotron losses.

[Embreus, Stahl & Fülöp, submitted to NJP (2016)]

Knock-on operator

Rosenbluth-Putvinski

- Primaries assumed to have infinite energy and zero pitch angle.
- Secondary runaways can be generated with higher energy than any of the existing runaways!
- No change to incoming particle in collision – does not conserve particle number, energy or momentum

[Rosenbluth and Putvinski, NF **37**, 1355 (1997)]

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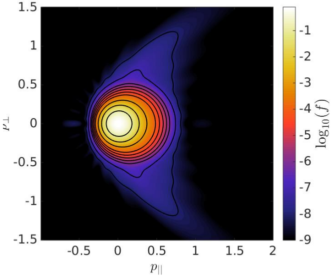

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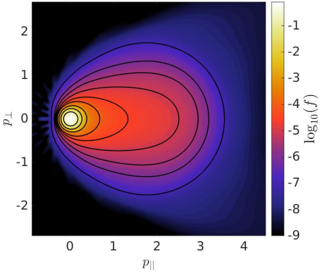

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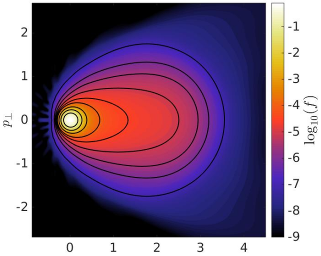
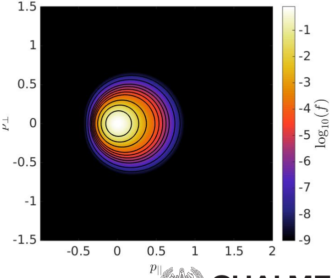


Chiu-Harvey operator

- Energy distribution of primaries accounted for, assuming zero pitch angle.
- Secondary particle momenta restricted by kinematics

[S.C. Chiu, et al., Nucl. Fusion **38**, 1711 (1998),
R.W. Harvey et al., Phys. Plasmas. **7**, 4590 (2000)]



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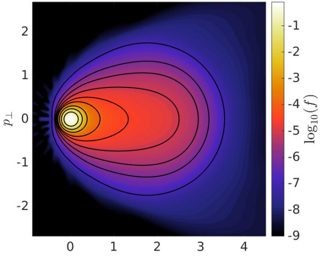

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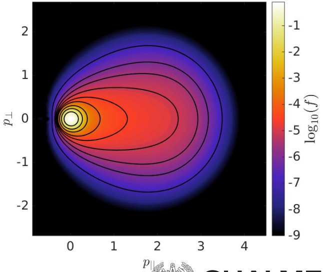
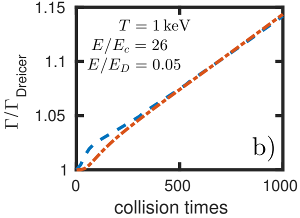


Comparison of the runaway growth rates



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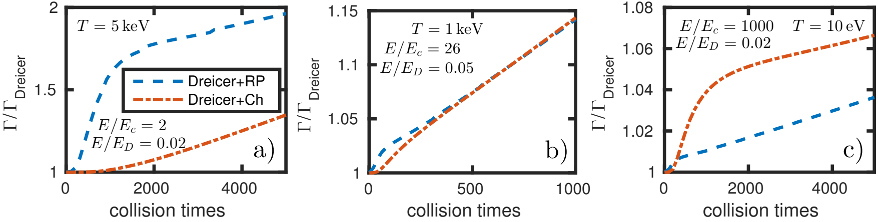
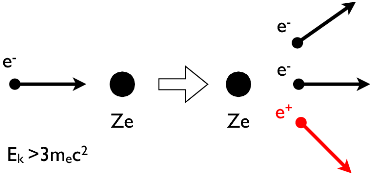


- More accurate operator (Chiu-Harvey) produces more runaways when the temperature is low and E/E_c large.
- Typical ITER disruption would lead to higher avalanche growth rates than the simpler operator (Rosenbluth-Putvinski) predicted.

[Stahl et al, to appear in NF (2016)]

Electron-positron pair production in tokamaks



- Large quantities of positrons are produced in disruptions.

- Like electrons, positrons experience acceleration from the electric field and slow down due to collisional friction and radiation reaction.
- Positrons are produced with high energies. Most of them run away and live long.
- Bremsstrahlung and synchrotron radiation from runaway positrons is peaked in the direction opposite from that of the runaway electrons.

[Helander et al, PRL (2003); Fülöp and Papp, PRL (2012)]

PHYSICS OF PLASMAS **21**, 064503 (2014)

What is the fate of runaway positrons in tokamaks?

Jian Liu,[1] Hong Qin,[1,2,a)] Nathaniel J. Fisch,[2] Qian Teng,[2] and Xiaogang Wang[3]

[1]*Department of Modern Physics and Collaborative Innovation Center for Advanced Fusion Energy and Plasma Sciences, University of Science and Technology of China, Hefei, Anhui 230026, China*
[2]*Princeton Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08543, USA*
[3]*School of Physics, Peking University, Beijing 100871, China*

- Probability of annihilation inside the plasma is negligible.
- Essentially all positrons will annihilate on the first wall.
- Annihilation spectrum could be used as a diagnostic tool.

Conclusions

Although runaway electrons have been well known for almost a century, new discoveries are continually made.

Runaway electrons expected to be a major problem in ITER

- Avalanche dominates in high current devices.
- Good modelling capacity is crucial!

Synchrotron and bremsstrahlung radiation reaction

- Reduces runaway growth rate for weak E fields.
- Can lead to bump-on-tail formation.

Opportunity to study relativistic phenomena

- Radiation reaction
- Pair production