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Runaway electron energy losses dominated by bremsstrahlung radiation in tokamak plasmas

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Outline

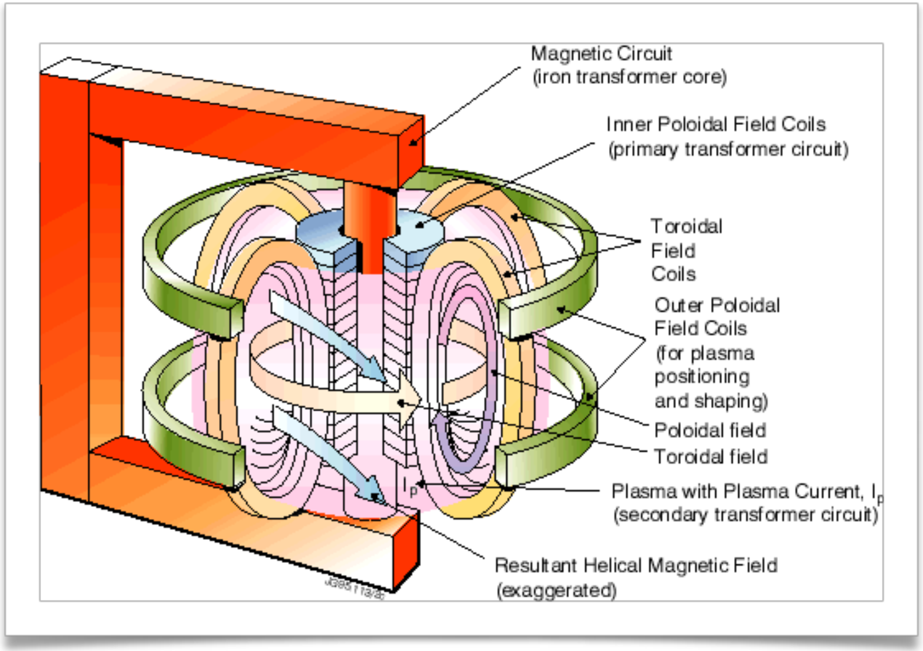
- Basic Concepts
  - Nuclear Fusion. Tokamak
  - Runaway electrons
  - Motivation: Runaway electrons during disruptions

- Energy limits for runaway electrons in tokamak plasmas
  - Runaway Energy Dissipation Mechanisms
  - Test Particle Model
    - Synchrotron Radiation
    - Bremsstrahlung Radiation
  - Conditions for Bremsstrahlung dominated energy losses
  - Disruptions generated runaway electrons

- Conclusions

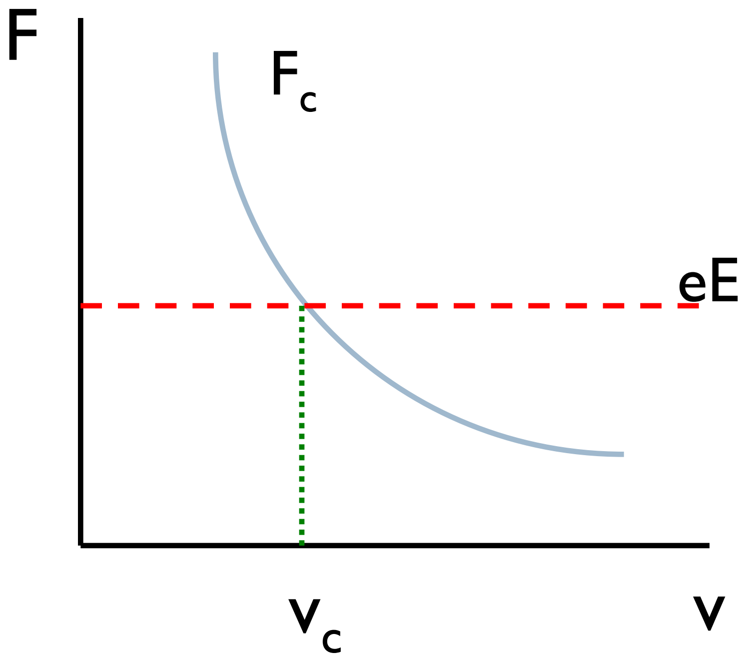
Nuclear Fusion. Tokamak

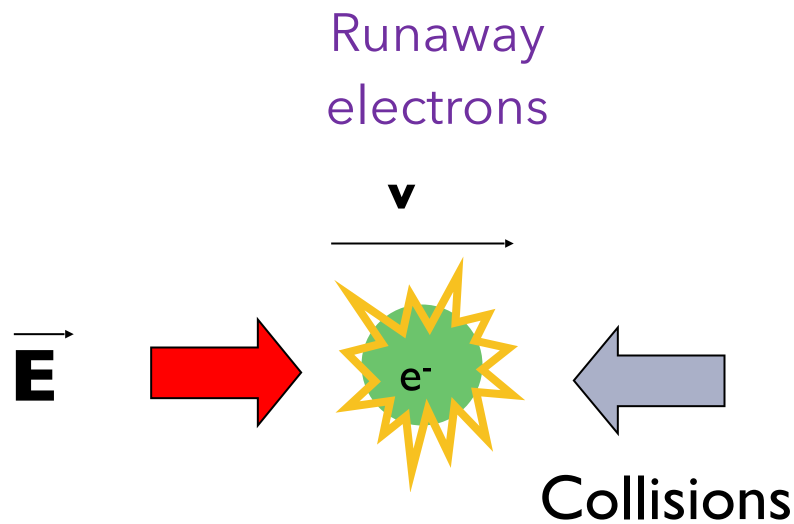
- Nuclear Fusion
- Magnetic confinement
- Tokamak devices
  - JET
  - ITER



Runaway Electrons

- Electrons in a tokamak plasma



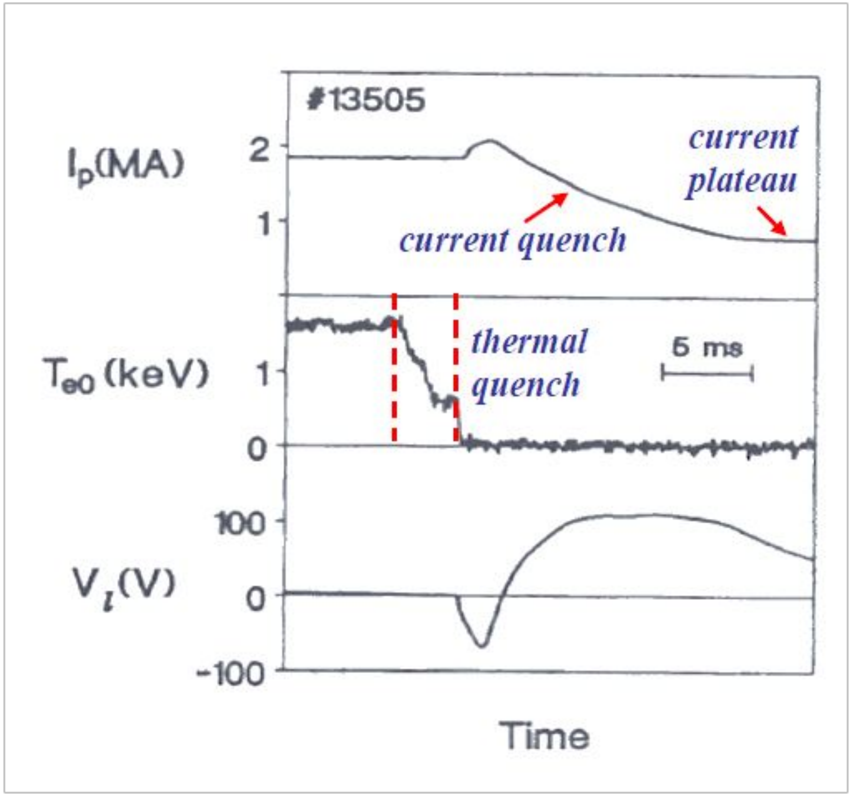


$v > v_c \rightarrow F_e > F_c$

Motivation: Runaway electrons during Disruptions

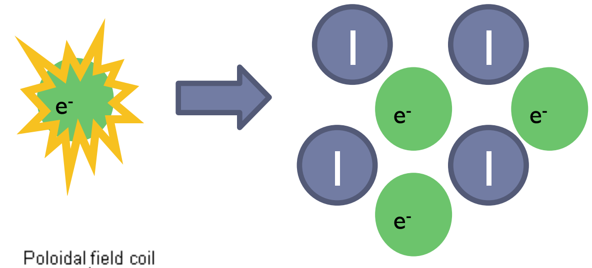
- Disruption: Violent unstable event leading to a sudden loss of confinement
- Te rapidly drops to very low values (few eV's)
- Plasma resistivity ($\eta \propto T_e^{-3/2}$) and electric field increase

- Generation of large amounts of runaway electrons which can be accelerated to very high energies (up to tens or hundreds MeV's)

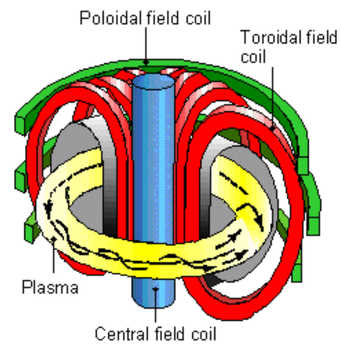


Energy Dissipation Mechanisms

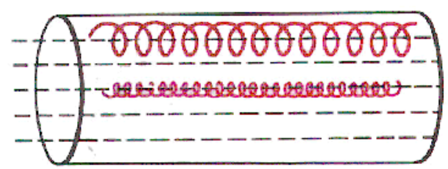
- Collisions with plasma particles



- Synchrotron Radiation: Radiation emitted when electrons follow a curved trayectory in the tokamak magnetic field
  - Gyromotion
  - Guiding center motion

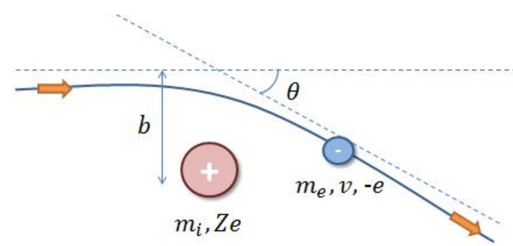


Guiding center motion



Gyromotion

- Bremsstrahlung Radiation: Radiation emitted when electrons are deflected due to interaction with plasma charged particles



Test Particle Model

- Simple model to describe runaway dynamics in energy and momentum space
- Only the interaction of the runaway electrons with thermal electrons and ions is considered
- Interaction with other runaway electrons is neglected ($n_r << n_e$)
- It allows to get simple estimates for:
  - Runaway electrons generation conditions
  - Maximum energy that runaway electrons can reach

Test Particle Equations

$$\frac{dp_{\parallel}}{dt} = eE_{\parallel}\frac{p_{\parallel}}{p} - \frac{n_c e^4 \ln \Lambda m_e}{4\pi\varepsilon_0^2}\gamma\left(Z+1+\gamma\right)\frac{p_{\parallel}}{p^3} - F_S\frac{p_{\parallel}}{p}$$

$$\frac{dp}{dt} = eE_{\parallel} - \frac{n_c e^4 \ln \Lambda m_e}{4\pi\varepsilon_0^2}\frac{\gamma^2}{p^3} - F_S\frac{p_{\parallel}}{p}$$

Syncrotron Radiation

Electric Field Acceleration

Collisional Term

$$F_S = \frac{2}{3} r_e m_e c^2 \left(\frac{v}{c}\right)^3 \gamma^4 \left\langle \frac{1}{R^2} \right\rangle$$

Bremsstrahlung Radiation

- Usually, for runaway electrons, bremsstrahlung radiation losses are much smaller than synchrotron radiation

- Disruption control and mitigation by means of injection of large amounts of high Z impurities (MGI: Massive Gas Injection)

- High density and ionic charge (*Z)* plasmas
- Large runaway bremsstrahlung losses

Test Particle Equations (including Bremsstrahlung Radiation)

$$\frac{dp_{\|}}{dt} = eE_{\|}\frac{p_{\|}}{p} - \frac{n_c e^4 \ln\Lambda m_e}{4\pi\varepsilon_0^2}\gamma\left(Z+1+\gamma\right)\frac{p_{\|}}{p^3} - \left(F_S + F_B\right)\frac{p_{\|}}{p}$$

$$\frac{dp}{dt} = eE_{\|} - \frac{n_c e^4 \ln\Lambda m_e}{4\pi\varepsilon_0^2}\frac{\gamma^2}{p^3} - \left(F_S + F_B\right)\frac{p_{\|}}{p}$$

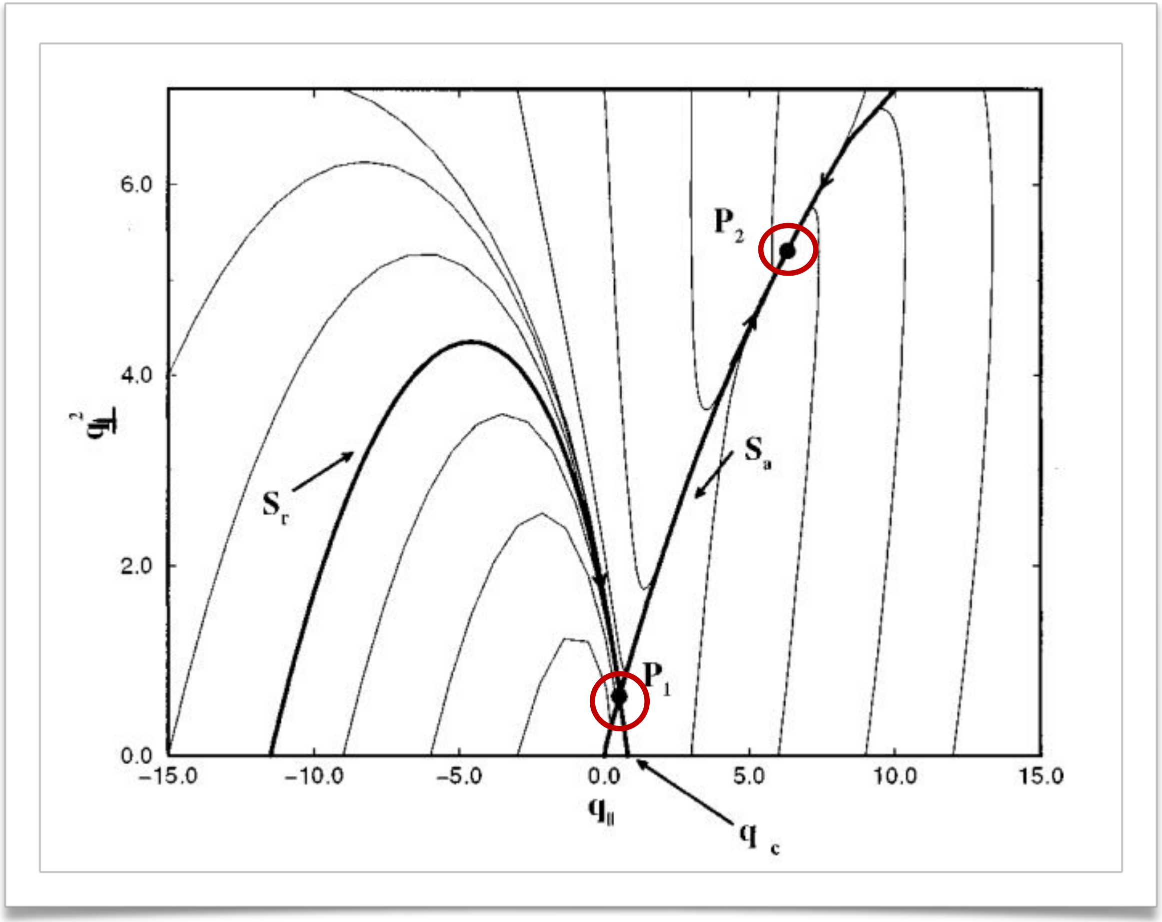
Radiation Term

Electric Field Acceleration

Collisional Term

$$F_B = \frac{4}{137} n_e \left(Z+1\right) m_e c^2 \gamma\; r_e^2 \left(\ln\left(2\gamma\right) - \frac{1}{3}\right)$$

Runaway Electrons Trajectories in Momentum Space



P2 Stable Focus

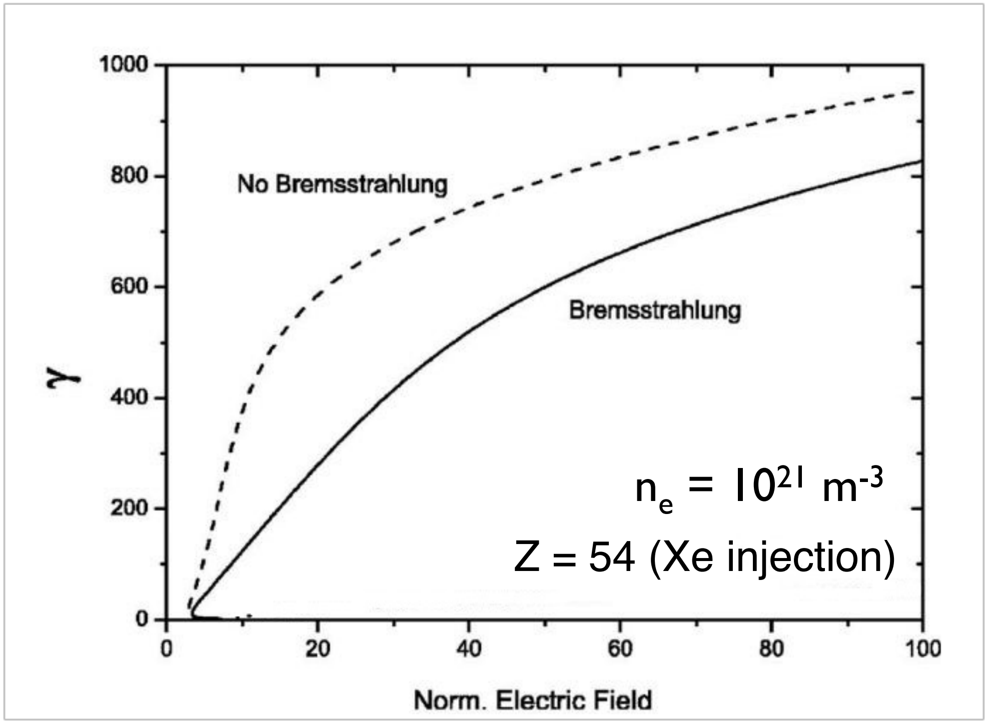
Maximum Runaway Energy

P1 Saddle Point

Critical Energy for runaway generation

Runaway Electron Energy

- Bremsstrahlung radiation can substantially reduce the maximum energy that the runaway electrons can reach if n_e and Z are large enough



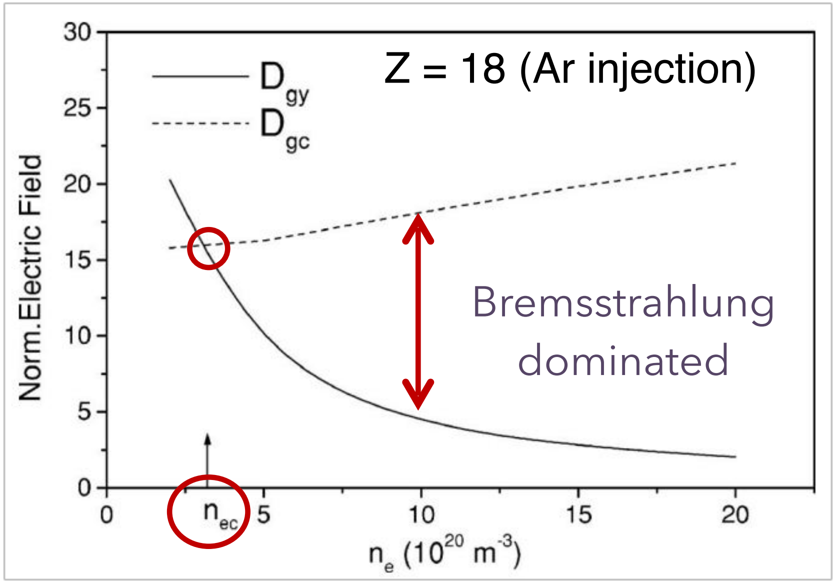
γ is the relativistic gamma factor:

$$E = (\gamma - 1) m_e c^2$$

Normalized electric field:

$$D \equiv E_{\|} \frac{4\pi\varepsilon_0^2 \, m_e c^2}{n_e \, e^3 \ln \Lambda}$$

Conditions for Bremsstrahlung dominated radiation losses



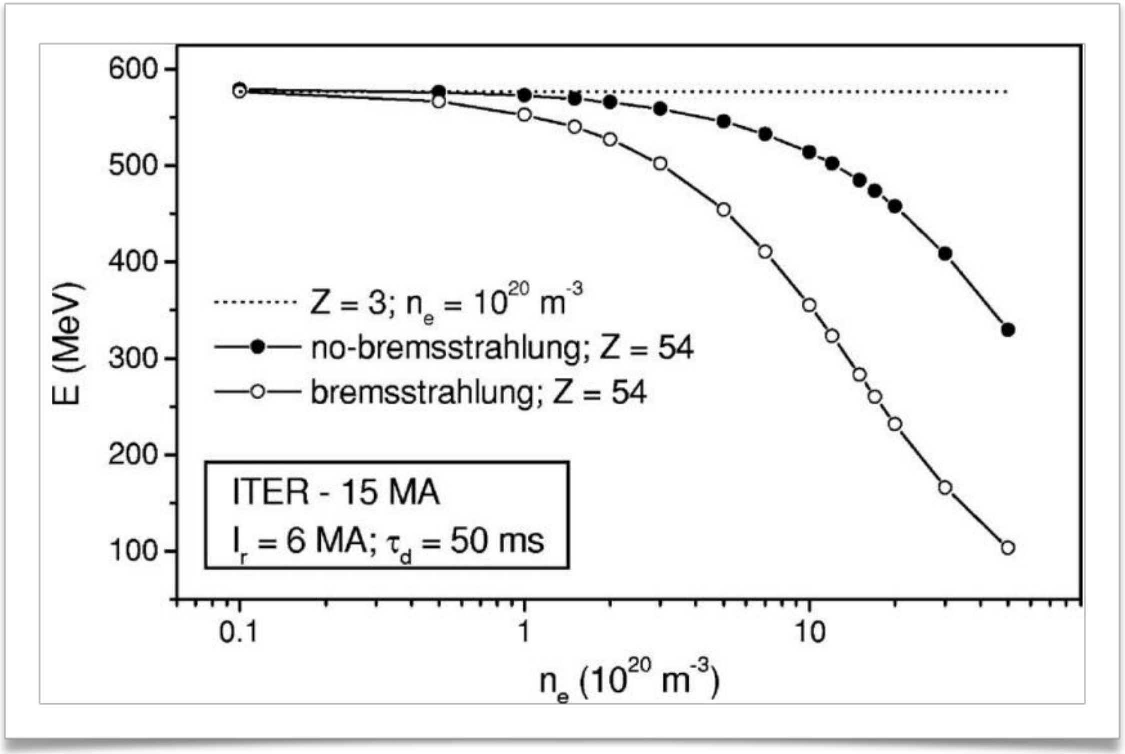
$$n_{ec} = 48 \frac{(\ln \Lambda)^{3/4}}{e^{7/4}} \frac{B_0^{3/2}}{(Z+1)R_0^{1/2}}$$

Critical (minimum) density for bremsstrahlung dominated energy losses

- Bremsstrahlung will dominate the runaway energy losses if:
  1. $n_e > n_{ec}$
  2. For $n_e > n_{ec}$, the normalizad electric field, D, must be in the range $[D_{gy}(n_e), D_{gc}(n_e)]$, where:
- D_{gy} : Electric field at which bremsstrahlung losses equal synchrotron losses due to electron gyromotion
- D_{gc} : Electric field at which bremsstrahlung losses equal synchrotron losses due to electron guiding center motion

Disruption generated runaway electrons

- It is predicted that, in ITER, for conditions of high density, n_e , and effective ion charge, Z, reached during disruption mitigation by MGI bremsstrahlung, radiation could dominate the electron energy losses, reducing the maximum energy that can be achieved by the runaway electrons



Conclusions

- Analysis of the dynamics in momentum-space of relativistic test runaway electrons including the accelerating electric field, collisions with the plasma particles as well as deceleration due to synchrotron and bremsstrahlung radiation losses

- Bremsstrahlung radiation could play a role as energy barrier mechanism for runaway electrons during disruption-mitigation experiments with injection of large amounts of high Z impurities

- The conditions (density and electric field) for bremsstrahlung dominated energy losses have been determined

Thanks for your attention!!