Runaway positrons in magnetized plasmas

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Positrons in tokamak plasmas

- Large quantities of positrons are produced in fusion plasmas.
  - What is the positron production rate in the presence of runaway electron avalanching?
  - What is the fate of the positrons (lifetime, runaway fraction)?
  - Can we detect them?
- Main conclusion:
  - Positrons in tokamaks are produced with high energies ($1 \ll \gamma_+ \ll \gamma_e$).
  - Most of them run away and live for several seconds.
  - Detection of synchrotron radiation may be possible.

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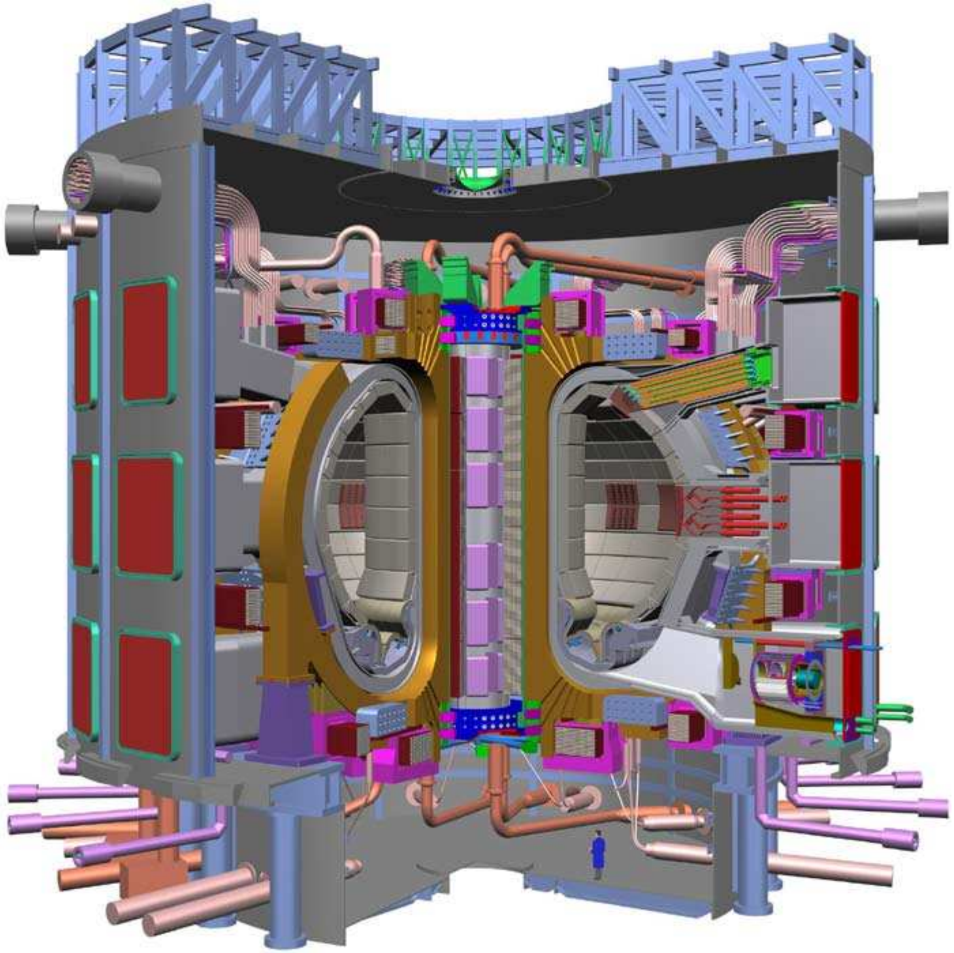
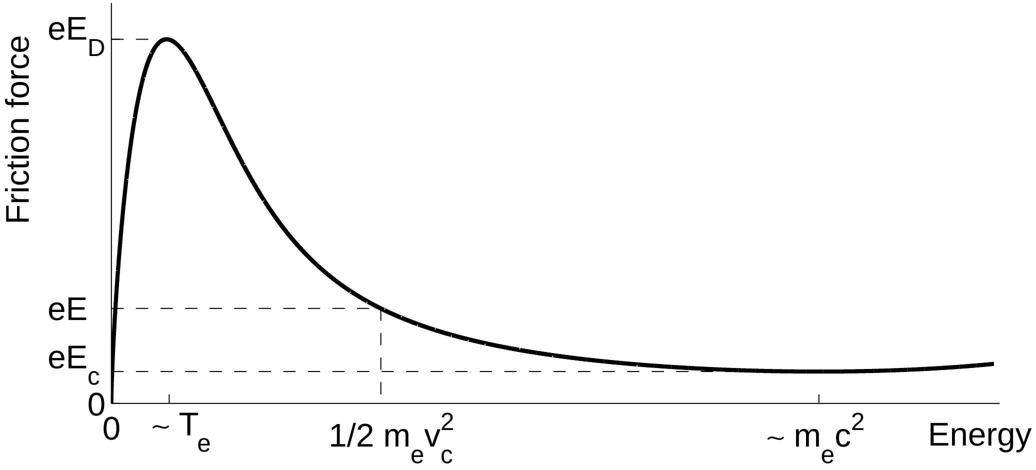


Under construction in France. First plasma in 2020.

The friction force

- Electrons are accelerated by an electric field and experience friction from collisions.
- Friction is non-monotonic function of velocity.
- For a given electric field there is a critical velocity, v_c, at which the friction equals the electric force.
- Runaway acceleration of some electrons if $E > E_c$
- Massive runaway if $E > E_D$ $(v_c = v_T)$

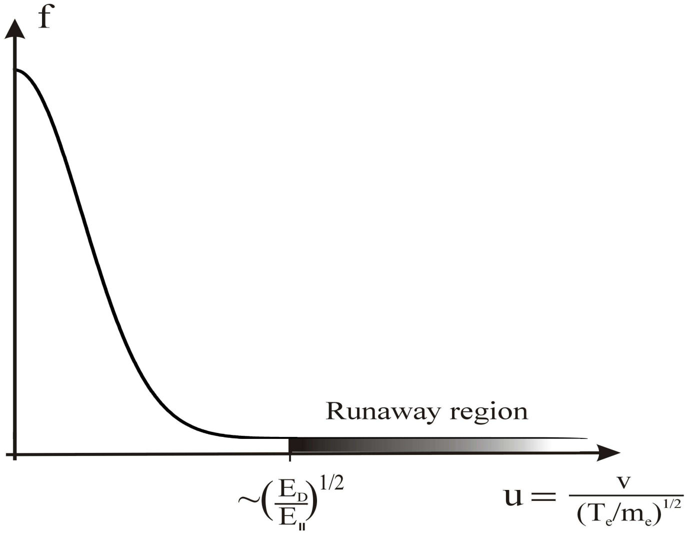
$$E_D = \frac{n_e e^3 \ln \Lambda}{4\pi\epsilon_0^2 T}$$



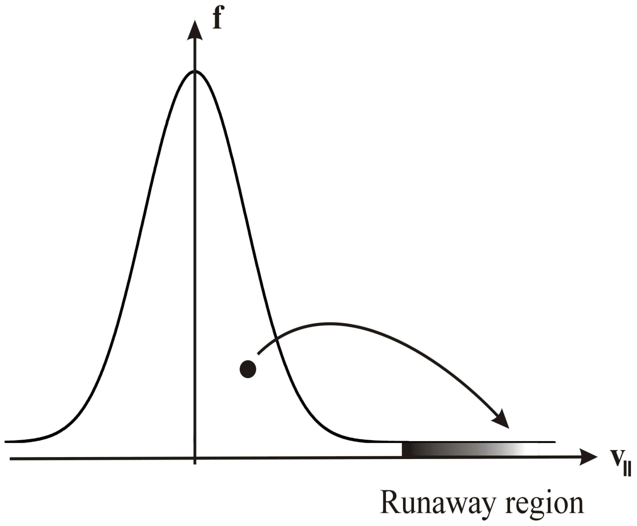
$$\frac{E_c}{E_D} = \frac{T_e}{m_e c^2} \ll 1$$

Primary and secondary generation of runaways

- Thermal electrons diffuse through the tail of the distribution.
- Results in a small runaway population.

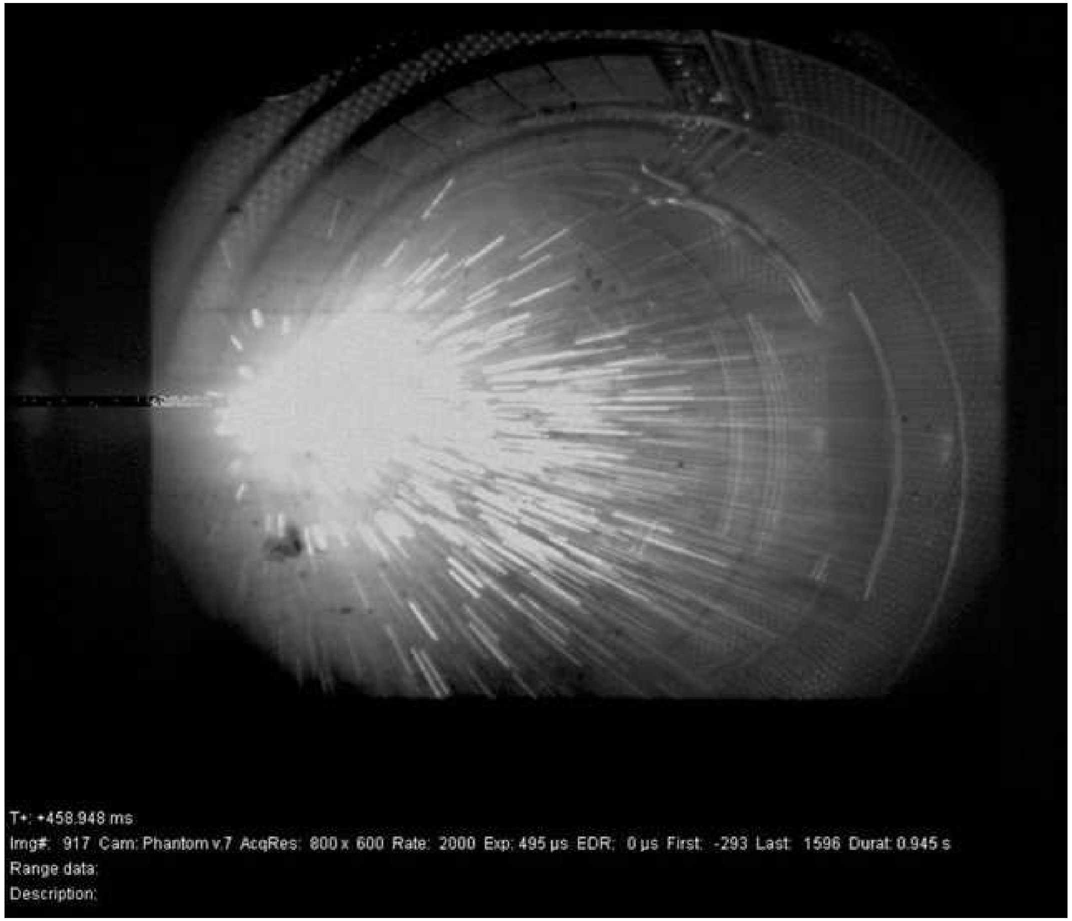


- In a close Coulomb collision an existing runaway electron can throw a thermal electron above the runaway threshold.
- Exponential growth of runaways.



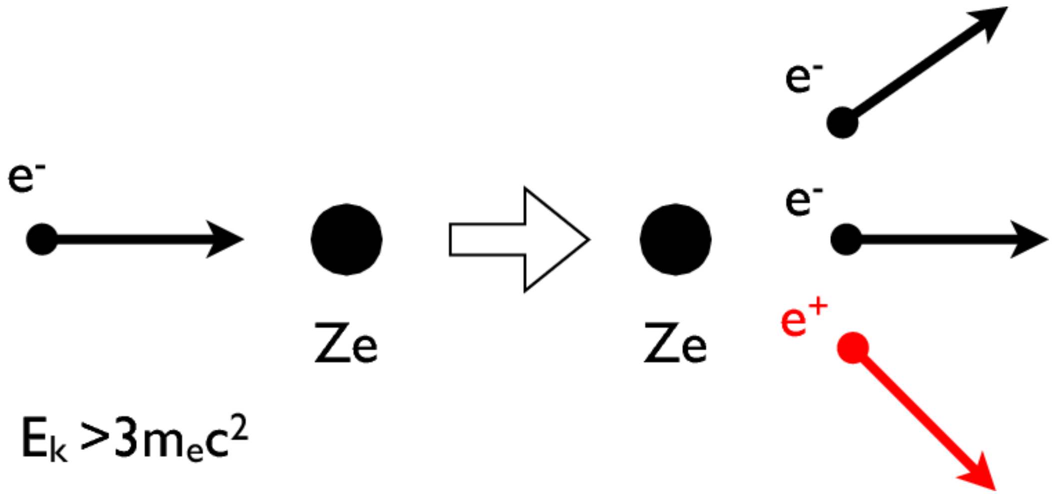
Runaway avalanches

- 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.
- If $E_{||} > E_c$ runaway electrons are created.
- The pre-disruption current is partly replaced by a current of runaway electrons ($I_r \simeq 1$ MA in medium-sized tokamaks).
- Typical runaway electron energy: 10-20 MeV.



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

Electron-positron pair production



- Estimated number of positrons in tokamaks with $I_r = 1$ MA: $N_p \simeq 10^{14}$ [Helander & Ward, PRL (2003)]
- This only takes into account collisions with hydrogenic ions, so it is probably an underestimate.
- Number increases in tokamaks with larger currents (such as ITER).

Runaway distribution function

- Distribution of secondary runaways:

$$f_e^{\rm RE} = \frac{n_r \hat{E}}{2\pi c_z p_{e\|} \ln\Lambda} \exp\left(-\frac{p_{e\|}}{c_z \ln\Lambda} - \frac{\hat{E} p_{e\perp}^2}{2p_{e\|}} \right),$$

where

$dn_r/dt = (E-1)n_r/c_z\tau$

[Rosenbluth & Putvinski, NF **37** (1997)]

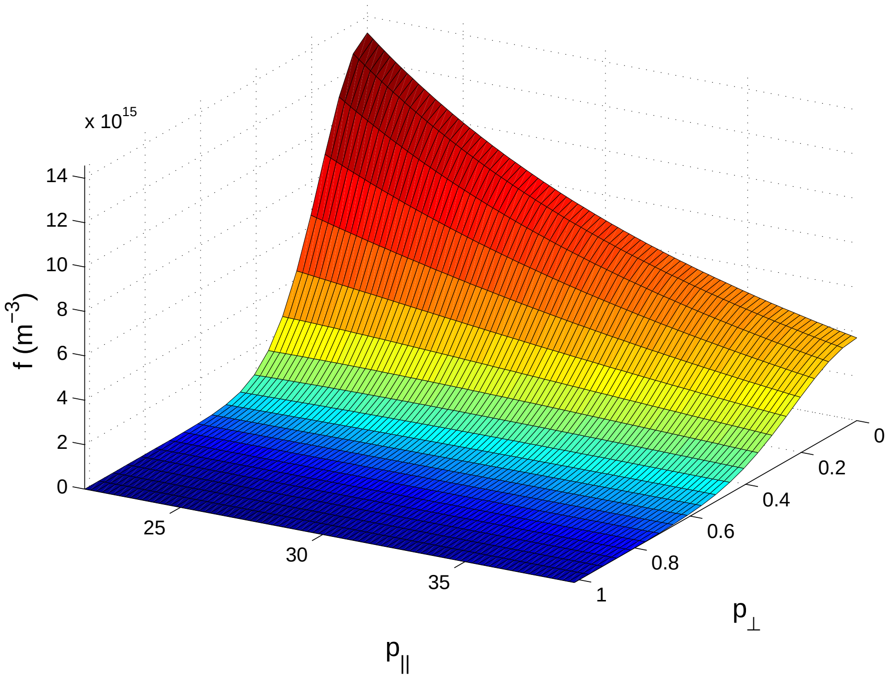
$E = e|E_\||\tau/m_e c$,

τ is the collision time for relativistic electrons,

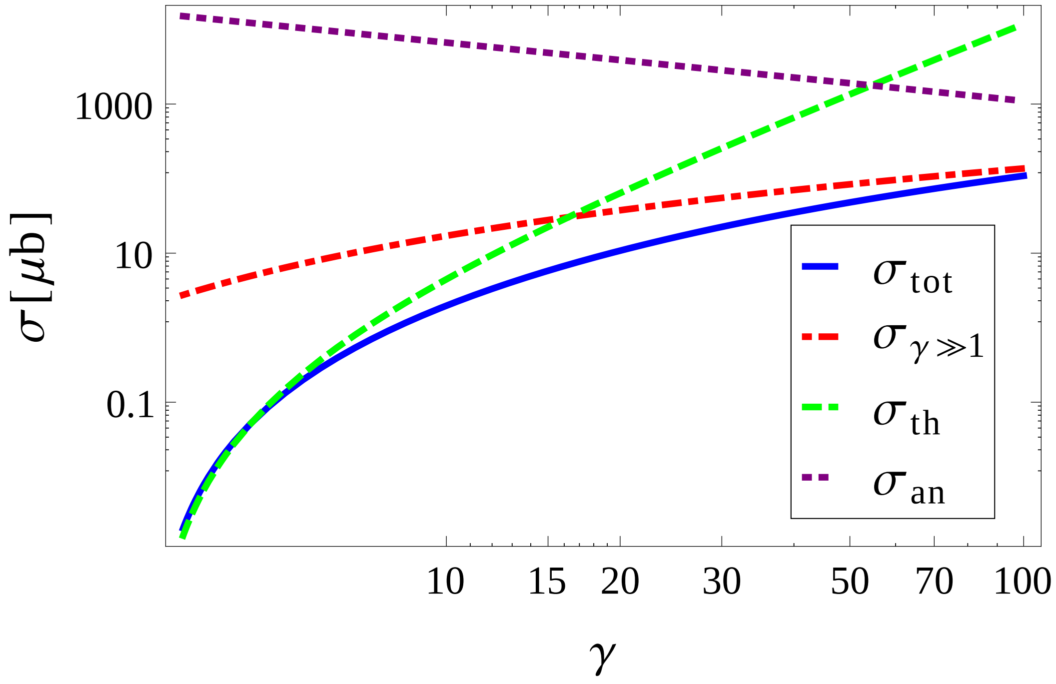
$\hat{E} = (E-1)/(1+Z_{\rm eff})$,

$c_z = \sqrt{3(Z_{\rm eff}+5)/\pi}$

$p = \gamma v/c$ normalized momentum



Positron production cross section



- Cross section for pair production (blue)

$$\sigma_{\text{tot}} = aZ^2 \ln^3\left(\frac{\gamma_e + x_0}{3 + x_0}\right)$$

$a = 5.22\ \mu b,\ x_0 = 3.6$

[D. A. Gryaznykh, Phys of Atomic Nuclei **61** (1998)]

- High-energy limit (red)

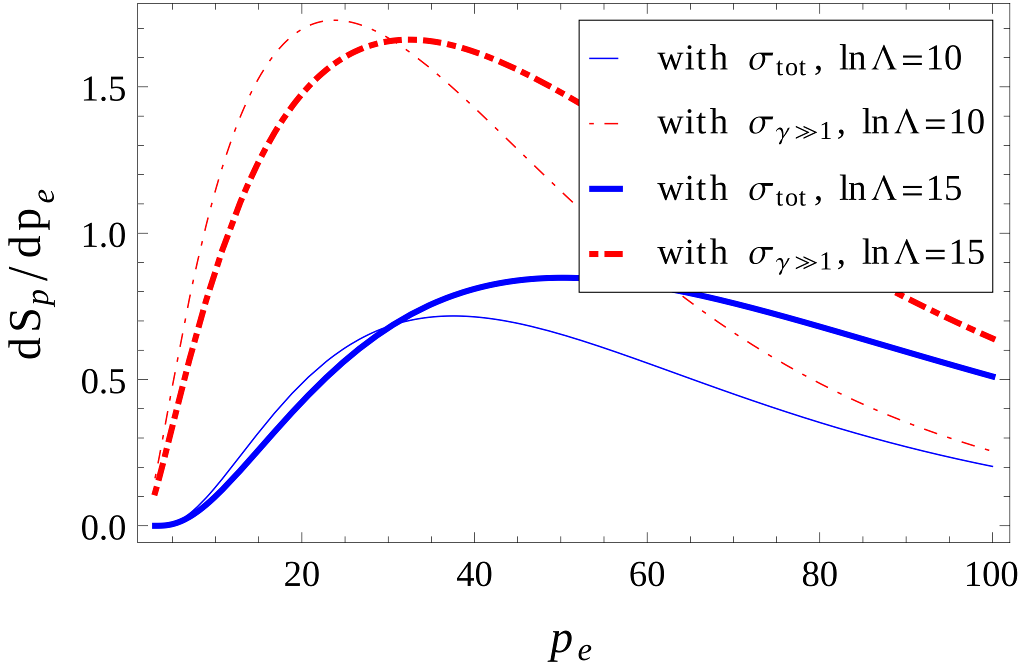
$$\sigma_{\gamma\gg1} \simeq \frac{28(Z\alpha r_e)^2}{27\pi} \ln^3 \gamma_e$$

- Threshold limit (green)

$$\sigma_{th} = 0.013Z^2(\gamma_e - 3)^3 \mu b$$

- Annihilation cross section (purple)

Positron production rate

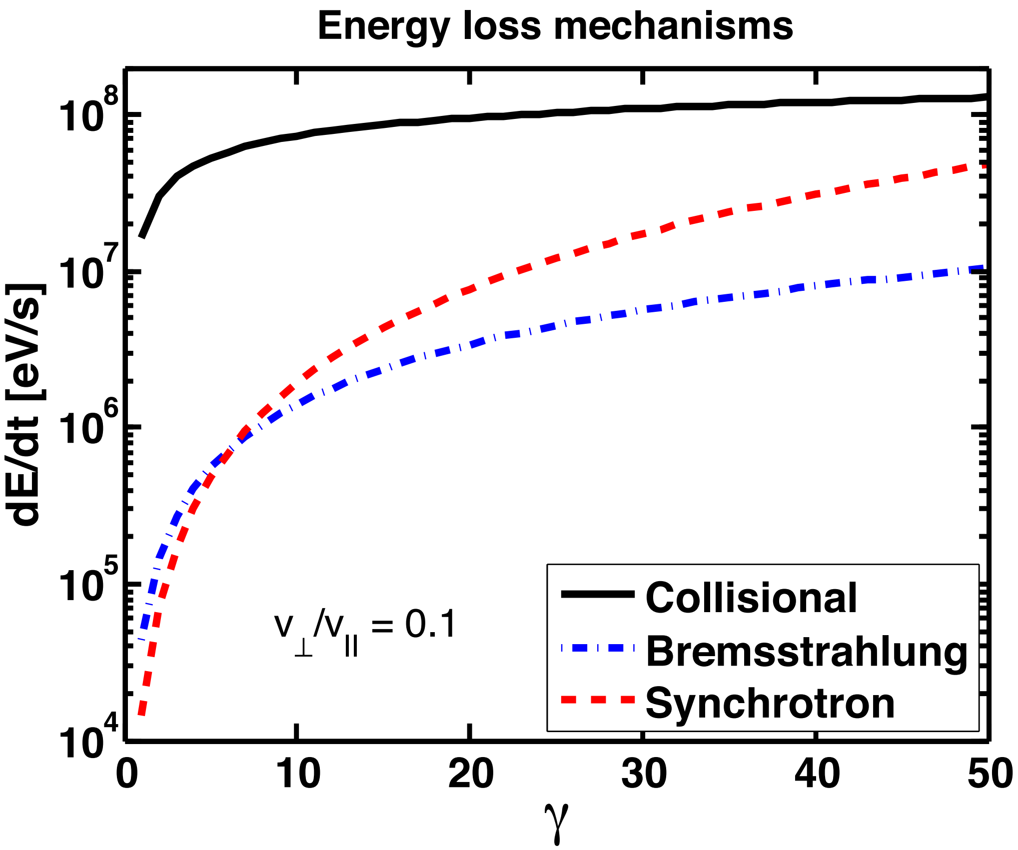


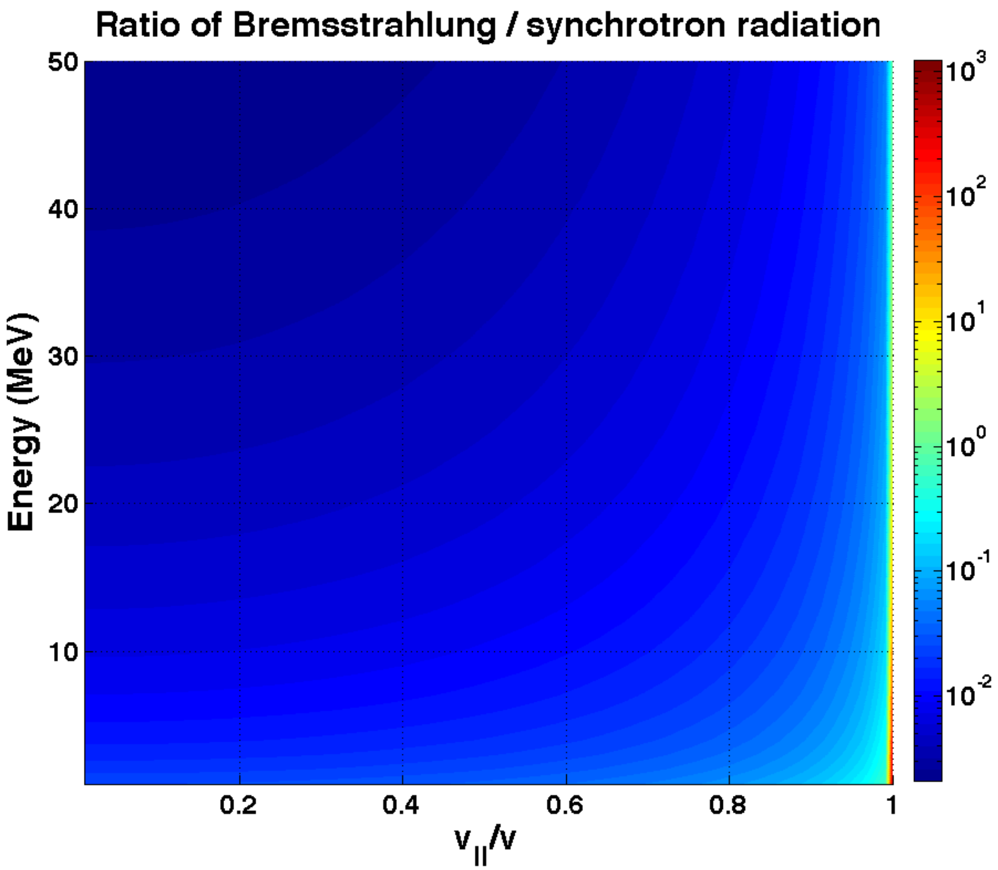
- The positron production rate $\mathrm{d}n_+/\mathrm{d}t = \int \frac{df_+}{dt} d^3p_+ \equiv S_p$ is

  $$S_p = n_i \int_{p_{\min}}^{\infty} f_e^{\mathrm{RE}} \sigma_{\mathrm{tot}} v_e \mathrm{d}^3 p_e,$$

  n_i is the number density of the ions.
- To take into account collisions with impurities and electrons this should be multiplied with $M_p \equiv 1 + n_e/n_i + \sum_z n_z Z^2/n_i$.
- 1 g of carbon distributed uniformly in a volume of about $80\ \mathrm{m}^3$, would correspond to a multiplicative factor of $M_p \simeq 450$.
- Number of positrons should be around 10^{15}.

Energy losses

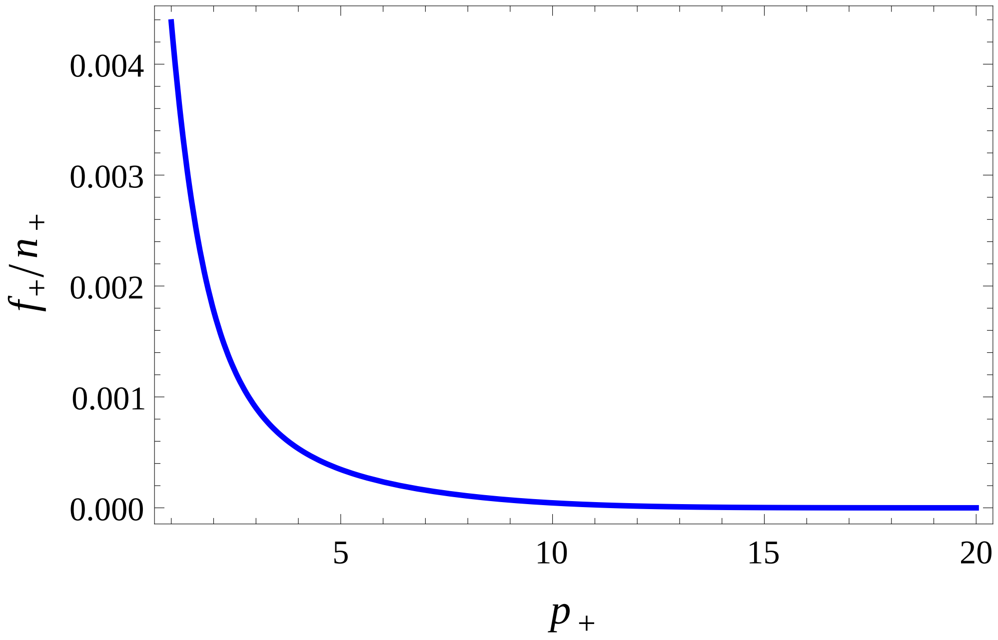




Steady-state positron distribution

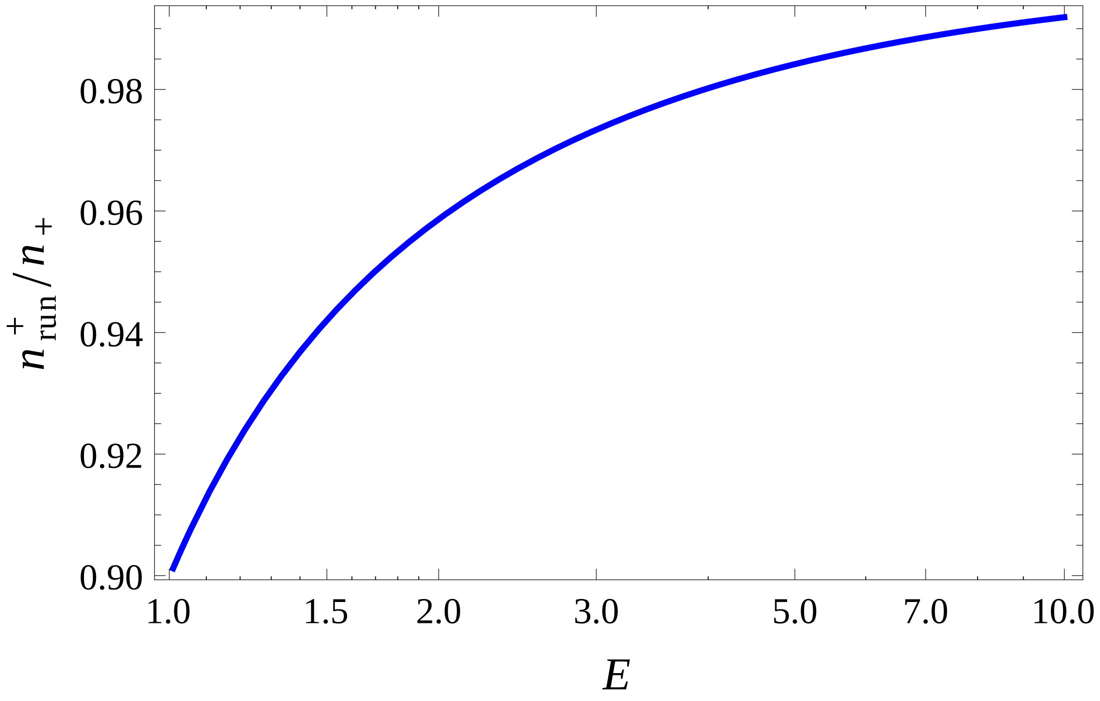
$$\frac{\partial f_+}{\partial t} = \frac{1}{\tau p_+^2}\frac{\partial}{\partial p_+}\left[(1+p_+^2)f_+\right] - n_e v_+ \sigma_a f_+ + s_p(p_+)$$

where $s_p \equiv df_+/dt = n_i \int f_e^{RE} \sigma_{tot} v_e \mathcal{F}(p_e, p_+) \mathrm{d}^3 p_e$ and $\mathcal{F}(p_e, p_+)$, is the probability distribution of positrons of momentum p_+ generated from electrons of energy p_e.



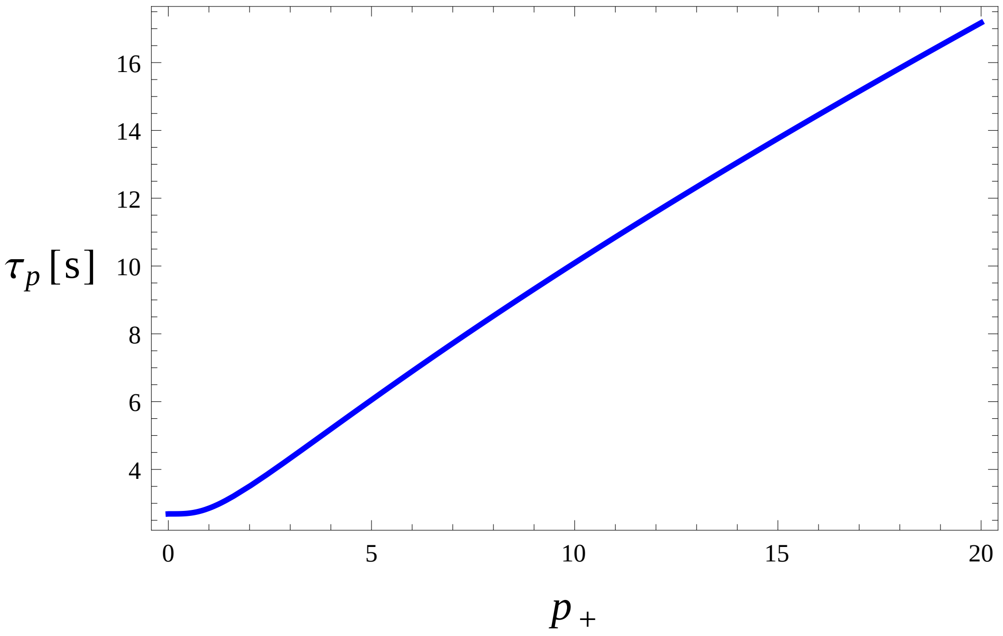
- Most positrons that survive the slowing down without annihilation will have momentum below $p_+ = 10$.
- Here, the presence of the electric field was neglected. But if $E > E_c$ a population of runaway positrons may be formed.

Runaway positrons



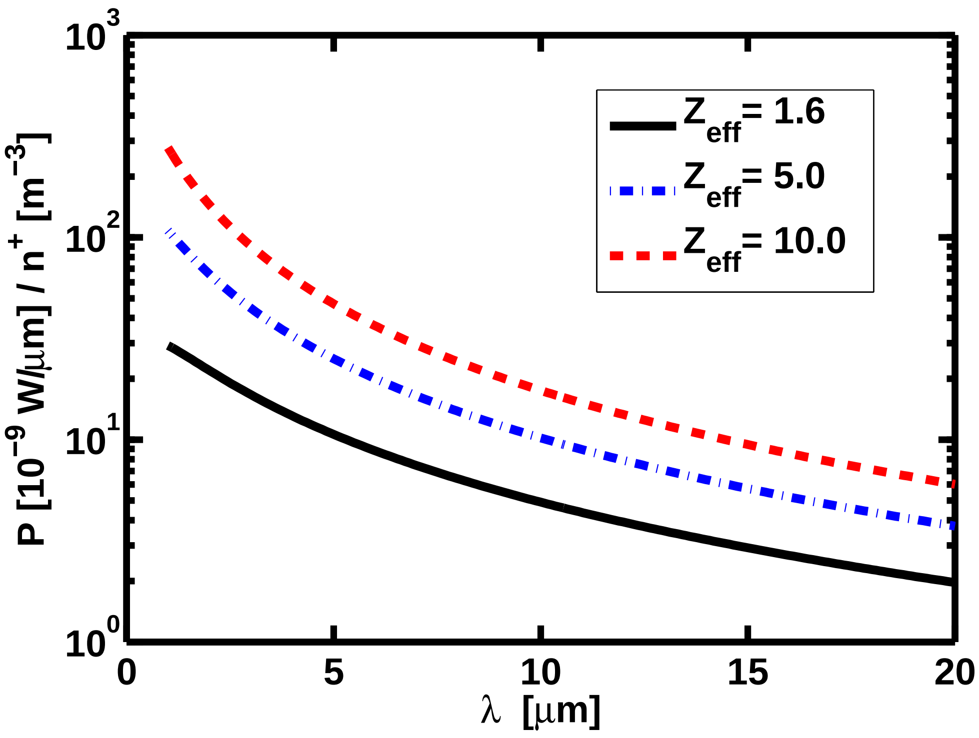
- The number of positrons that run away can be estimated by calculating how many positrons are born above the critical velocity $v_c = c/\sqrt{2E}$.
- $n^+_{run} = 4\pi \int_{p_c}^{\infty} f^+(p^2 - p_c^2)dp$
- For most positrons $p_c \ll p_+ \rightarrow$ almost the whole positron population can be expected to run away $n^+_{run} \simeq n_+$.

Lifetime and possibility for detection

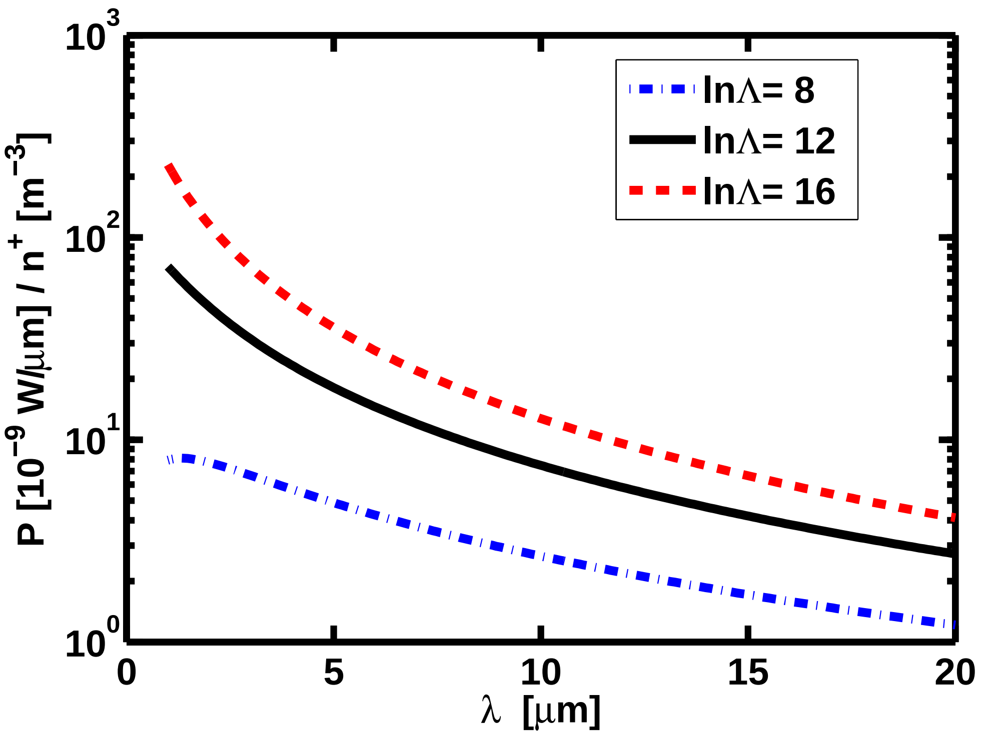


- The lifetime of a positron can be estimated from the annihilation cross section $\tau_p = 1/n_e v_+ \sigma_a$.
- Annihilation radiation is hard to detect because the Bremsstrahlung from the runaway electron population is larger.
- Bremsstrahlung and synchrotron radiation from runaway positrons is peaked in the direction opposite from that of the runaway electrons.

Synchrotron radiation



Effective charge



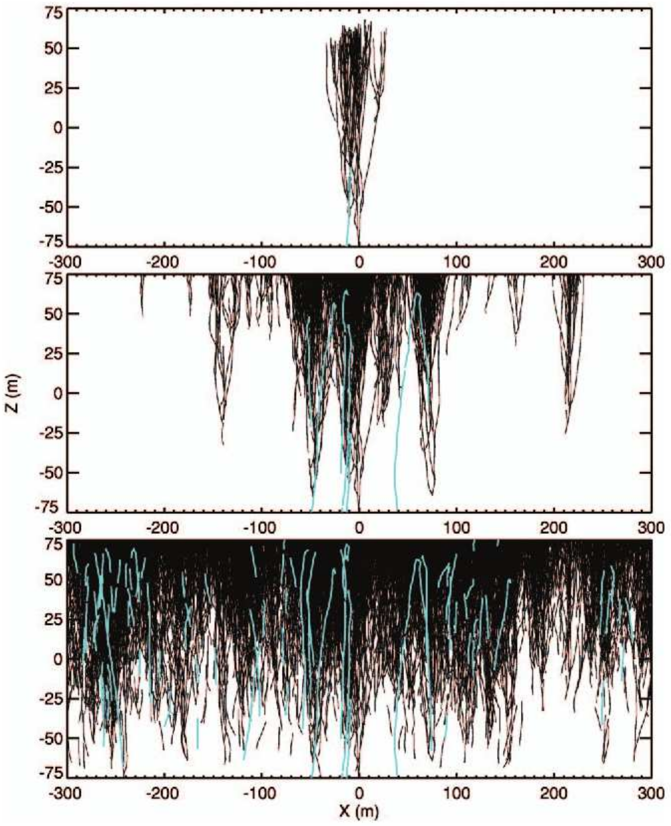
Coulomb logarithm

Positrons in thunderstorms

- Runaway electron avalanches play a role in lightning initiation.

  (Gurevich et al, Phys. Lett. A, 1992)

- Runaway avalanching provides mechanism for breakdown at 2 kV/cm, rather than the conventional threshold for breakdown in air 23 kV/cm.
- Positrons are generated and they produce new runaway electrons.
- Feedback of positrons have been shown to be important in lightning initiation (in simulations).



Monte Carlo simulations showing runaway avalanches for air with electric field $E = 750$ kV/m. Blue trajectories are positrons. [From Dwyer, Phys. Plasmas (2007).]

Conclusions

- Runaway avalanching is an issue of great concern in tokamaks. There are still many unsolved questions regarding generation, propagation and losses of runaway electrons.
- Positrons in tokamaks are produced with high energies ($1 \ll \gamma_+ \simeq \gamma_e$). Most of them run away and live long.
- There should be more than 10^{15} positrons in a typical tokamak disruption with runaway avalanching.
- Detection of synchrotron radiation (with wavelengths of a few μm) from runaway positrons may be possible.
- Since the radiated power and spectrum shape are sensitive to the impurity concentration, temperature and other parameters, positron radiation can be a diagnostic tool to understand the properties of the discharge.