Important Parameters for Runaway Electron Physics in ITER

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Significance of Issue

The plasma current in ITER cannot be allowed to transfer from thermal to relativistic electron carriers.

The potential for damage is too great for even a comprehensive test of the mitigation strategy.

Theory and modeling must be developed for assurance that ITER can be operated at mission-relevant currents, >5MA, without excessive danger to the device. ***Theory must be believed!***

Fundamental Mechanisms

1. Drag force of background electrons

   Background electrons exert a drag force on super-thermals

$$f_{drag} \propto \frac{n_b}{(\mathrm{v}/c)^2} \ln \Lambda .$$

   Runaway requires the electric field satisfy $E_{\parallel} > f_{drag} / e$.

   Note $\ln \Lambda$ *comes from singularity in the small scatters that give the drag.*

2. Minimum drag force

   Minimum drag force, $\mathrm{v} \to c$, defines the Connor-Hastie electric field $E_{CH} \equiv (f_{drag})_{\min} / e$. Connor & Hastie, NF **15**, 415 (1975)

3. Kinetic energy required for runaway $K_r > m_e c^2 \dfrac{E_{CH}}{E_{\parallel}}$

   Without pitch-angle scattering $K_r \approx m_e c^2 E_{CH} / E_{\parallel}$

4. Effect of pitch-angle scattering on runaway energy K_r

Anisotropy of low energy runaways is $\varepsilon_a \approx \frac{1}{1+Z}\frac{E_\parallel}{E_{CH}} \le 1$

Runaway requires $\frac{dK}{dt} = \mathrm{v}\left(\varepsilon_a e E_\parallel - f_{drag}\right) > 0;\quad f_{drag} = \frac{m_e c^2}{K} e E_{CH}$

$$\frac{K_r}{m_e c^2} \approx (1+Z)\left(\frac{E_{CH}}{E_\parallel}\right)^2 \ge \frac{E_{CH}}{E_\parallel}.$$

Effect of pitch-angle scattering scales as $1/\gamma$ *and is not important for the typical runaway with* $\gamma = \bar{\gamma} >> 1$.

5. Runaways create new runaways giving an avalanche

The same collisional cross section that gives the drag force implies a high-energy electron can scatter low energy electrons to high energy.

$$\frac{d\ln n_r}{dt} \approx \frac{eE_{CH}}{2\ln\Lambda}\frac{c}{K_r}.$$

Jayakumar, Fleischmann, & Zweben, Phys. Lett. A **172**,447 (1993)

This scattering is non-singular so no $\ln\Lambda$*.*

6. Relativistic electrons are accelerated as $\frac{d\gamma}{dt}m_e c = eE_{\|}$.

Runaways develop a distribution function $f \propto \exp(-\gamma/\bar{\gamma})$,

where $$\bar{\gamma}-1 \approx \frac{d\gamma/dt}{d(\ln n_r)/dt} \approx 2\ln\Lambda\frac{E_{\|}}{E_{CH}}\frac{K_r}{m_e c^2} > 2\ln\Lambda$$

Pitch-angle scattering increases K_r*, which increases* $\bar{\gamma}$*.*

Four Parameters That Define Electron Runaway

1. The local loop voltage $V_\ell \equiv \left(\frac{\partial \psi_p}{\partial t} \right)_{\psi_t}$.

   The slippage of the external poloidal flux relative to the enclosed toroidal flux. *(Runaways tied to toroidal flux when I/G<<1.)*

   Runaway not possible due to drag of background electrons with density n_b in units of $10^{20}/m^3$ unless

   $V_\ell > V_{CH} \sim 3n_b$ Connor & Hastie, NF **15**, 415 (1975).

   Requires that plasma be cooled to T_e<1kev.

2. Poloidal flux change $\psi_{e\text{-}fold}$ >2.3 V·s for an e-fold in runaways.

Passing electrons conserve $p_\varphi = \gamma R m_e \mathrm{v}_\varphi + e\psi_p / 2\pi$

$\psi_{e\text{-}fold}$ given by $\delta\psi_p$ required to increase γ to the runaway average, $\bar{\gamma}$.

$\psi_c \equiv 4\pi R \ln\Lambda \dfrac{m_e c}{e} \sim 2.3\mathrm{V}\cdot\mathrm{s}$ in ITER,

$$\psi_{e-fold} \approx \left(\frac{K_r}{m_e c^2} \frac{E_\parallel}{E_{CH}} \right) \psi_c \geq \psi_c .$$

3. Ratio exp(-σ_s) of initial (seed runaways) to the number of runaways required to carry the plasma current.

   Runaway fraction required to carry current, e^{-9}, is obvious.

   Tail of pre-cooling Maxwellian gives a large source, $\sigma_s \sim 1$, unless plasma is cooled slowly. Eliminated when $\tau_{cool} \geq 40\text{ms}$.

   Most difficult source to control is Compton scattering of electrons from γ-rays emitted by activated ITER walls at an energy above the runaway energy. *Importance unclear; need γ-ray flux vs. energy.*

   When plasma is cold Dreicer (Maxwellian) runaway is irrelevant.

4. Initial flux $\psi_0 \approx \mu_0 RI \sim 100\,\text{V}\cdot\text{s}$ between magnetic axis & walls.

   When $V_\ell >> V_{CH}$ and $\dfrac{\psi_0}{\psi_{e-fold}} > \sigma_s$, current transfer occurs.

Three Important Time Scales

1. Time $\gamma\tau_{CH}$ for an electron to join Maxwellian, $\tau_{CH} \equiv \frac{m_e c}{eE_{CH}}$.

   τ_{CH}~22.7ms/n_b, where γ is relativistic factor & n_b background density in $10^{20}/m^3$.

2. Time τ_R for runaway distribution to reach a steady-state, *exponentially increasing*, form.

   Requires a few $\psi_{e\text{-}fold}$'s

3. Time $\tau_T = \frac{\sigma_s \psi_{e-fold}}{V_\ell}$ required to transfer current to runaways.

   Existing theories make simplifying assumption $\tau_T >> \tau_R$, which is not valid unless $\sigma_s >> 1$.

Important Physics for Avoiding Transfer

1. Angular scattering by high-Z impurities when $1+Z > V_\ell / V_{CH}$.

   Critical energy for runaway: $K_r / m_e c^2 \sim (1+Z)(V_{CH}/V_\ell)^2$.

   $\psi_{e\text{-}fold}$ increased by a factor $(1+Z)V_{CH}/V_\ell$.

2. Faster direct loss of relativistic electrons than $\psi_{e\text{-}fold}/V_\ell$.

   Broken magnetic surfaces or trapped electron drifts.

   ITER walls could have been designed so induced currents of $\delta\psi_p$ would destroy magnetic surfaces. (Would also reduce forces on walls.)

3. Synchrotron radiation *(in ITER of marginal importance)*.

4. Formula for avalanche source

   Rosenbluth-Putvinski approximation probably not sufficiently accurate for a reliable $\psi_{e\text{-}fold}$. Paper derives more accurate formula.

Implications for Disruption Mitigation

To avoid halo currents, plasma current must be brought down faster than 150ms, so edge q rises rather than drops. Implied loop voltage V_ℓ~ (100 V·s/150 ms)/2 ~350 Volts>>V_{CH}.

Present plan is to cool plasma even quicker, 10's ms, which will leave many hot-Maxwellian electrons above runaway energy.

Not studied as part of mitigation design: (1) slow cooling, ~40 ms, to avoid Maxwellian runaway and (2) use of very high-Z impurities to increase runaway energy K_r and $\psi_{e\text{-}fold}$.

Requires staged impurity injection.

Pre-emptive slow cooling of disruption-prone plasmas may be needed to prevent unacceptable runaway damage to ITER.

Goals for Theory Program on Runaways

1. Increase credibility of runaway avoidance on ITER

   Comprehensive tests of runaway avoidance under ITER-like conditions cannot be made on existing tokamaks and would be too dangerous to perform on ITER without assurance that a large current transfer would not occur. ***Theory must be believed!***

2. Provide analysis and suggest experiments for validating the fundamental physics of runaway avoidance.

   Until the runaway current approximates the full plasma current, runaway production is passive. Knowing how plasma conditions can be controlled in plasmas without runaways is critical.

   Physics, such as synchrotron radiation and instabilities, that appear unimportant in ITER may be important in experiments.