RUNAWAY ELECTRONS AND ITER

(Summary of a paper submitted for publication)

Allen Boozer

Columbia University July 21, 2016

Work supported by DoE Office of Fusion Energy Science grant De-FG02-03ER54696

Theory and simulation are essential for ensuring that relativistic runaway electrons will not prevent ITER from achieving its mission.

The runaway phenomenon is unique because of

The potential for damage,

The magnitude of the extrapolation,

The importance of the atypical---once in a 1000 shots.

The planed injection of impurities is associated with magnetic surface breakup; avoidance is subtle; mitigation may be impossible.

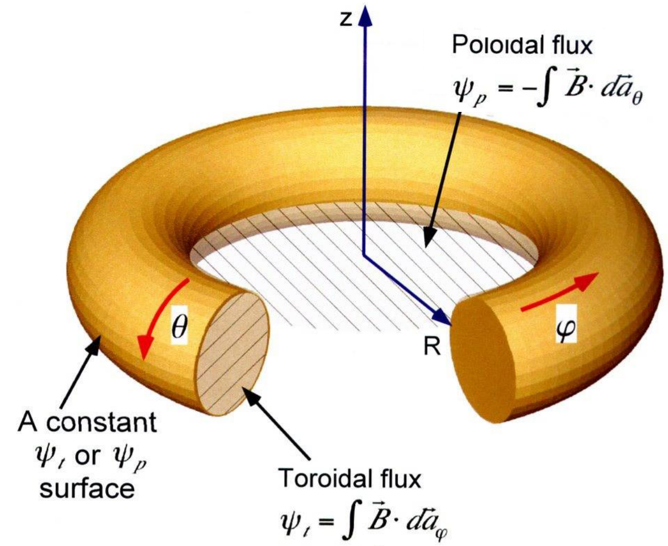
Runaway Electrons May Arise When

$$\textit{Loop voltage } V_\ell \equiv \left(\frac{\partial \psi_p}{\partial t}\right)_{\psi_t} \gtrsim 2.9 \frac{n}{10^{20}/m^3}\text{Volts.}$$

1. Due to a thermal quench, ~1ms, as part of a natural disruption.

   ITER poloidal flux $\psi_p \approx 70$V·s; removal time is 50-150ms.

$$V_\ell \gtrsim 500\text{Volts}$$



2. As a result of a mitigation strategy to prevent the plasma drifting into a wall. Poloidal flux removal time < 150ms.

$$V_\ell \gtrsim 500\text{Volts}$$

If poloidal flux is not removed this quickly a strong halo current can arise along with a relativistic electron current.

Absence of a Maxwellian Runaway *(optimistic result)*

When electrons are cooled sufficiently slowly that they remain close to Maxwellian, a runaway cannot occur in ITER.

Runaway only possible when $\left|eE_{||}\right| = \left|e\eta j_{||}\right| > \frac{eE_{ch}}{2\epsilon_{max}T}$.

$$\epsilon_{max} \equiv \left(\tfrac{1}{2}mv^2/T\right)_{max} \approx 50, \text{ maximum kinetic energy.}$$

Number of tail electrons in a Maxwellian $\mathcal{F}_{tail}^{(Max)}(\epsilon) = \frac{2\sqrt{\epsilon}}{\sqrt{\pi}} e^{-\epsilon}$.

For $\epsilon > \epsilon_{max}$, either less than one electron in the plasma or not enough possible e-folds to increase their number to be significant.

Condition for Maxwellian Runaway

Runaway requires $T < \epsilon_{max}^2 \left(\frac{4}{3}\frac{0.51}{\sqrt{2\pi}}\right)^2 \left(\frac{j_{||}}{j_c}\right)^2 \lesssim 4\text{eV}$, where $j_c \equiv enc$.

$j_{||}/j_c \sim 2\times 10^{-4}$

Maintenance of Maxwellian requires sufficiently slow cooling;

$$\text{Cooling time} > \tau_{th} = \frac{2^{\frac{3}{2}}}{3}\left(\frac{\epsilon_{max} T}{mc^2}\right)^{\frac{3}{2}} \frac{1}{\nu_{ch}}$$

$$\lesssim 25\text{ms}, \qquad \nu_{ch} \equiv \frac{eE_{ch}}{mc}.$$

Minimal cooling time for maintaining a Maxwellian is

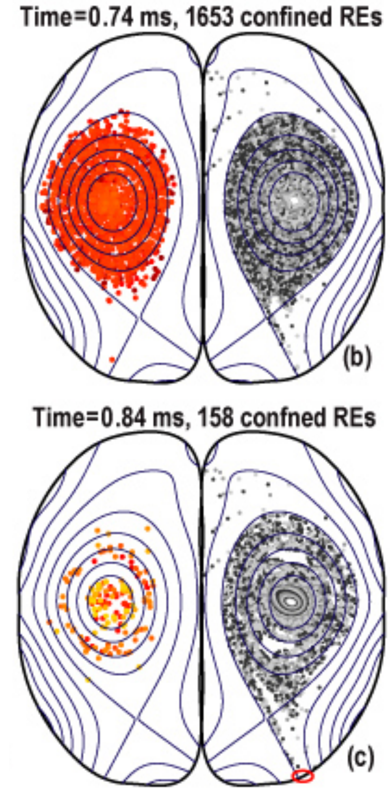
much shorter than the fastest time required for poloidal flux removal, ~150ms, but

much longer than thermal quench time, ~1ms.

Magnetic Surface Breakup

Basis of present ITER strategy for avoidance

If all magnetic field lines in the plasma strike the walls within 100's of toroidal circuits, runaway electrons are lost too rapidly for relativistic electrons to be an issue (another optimistic result).



Izzo et al, PPCF2012

Unfortunately, **tubes of magnetic flux that do not intercept the walls can remain in the cores of islands and near the plasma center.**

Non-intercepting flux tubes are places where energetic electrons can be stored and accelerated to relativistic energies.

When outer surfaces reform before the flux tubes dissipate, electrons can dump in ~0.5ms along a narrow flux tube ~150cm^2.

Fast Magnetic Relaxations

The voltage spike accompanying a thermal quench gives

the time scale, ~1ms, of the magnetic relaxation and

the completeness of the magnetic helicity conserving relaxation.

Flux change during the thermal quench, $\delta\psi_p \lesssim \Psi_t/9 \approx 13$V·s, is sufficient to accelerate electrons in non-intercepting flux tubes to relativistic energies and exponentiate their number.

ITER operability is determined by worst event in about a year, ~1000 shots.

Plasma Cooling

Cross-field transport: Upper limit is Bohm transport--too slow.

Magnetic surface breakup: Maxwellian maintenance is impossible; flux tubes that do not intercept walls allow electron acceleration.

Radiation: In principle highly controllable and consistent with a rapid ITER shutdown, <<150ms, but requires extreme care:

1. Cooling rate can increase as T_e drops, which can cause the Maxwellian to be broken and produce a runaway.
2. Radial profile control required to (a) cool central T_e and (b) avoid loss of magnetic surfaces (tearing instabilities).
3. Impurity delivery consistent with required $T_e(r,t)$ probably not producible by massive gas injection or shattered pellets.

Circumscribing Quantities

Four quantities circumscribe what is possible

1. Number of seed electrons,
2. Kinetic energy required for runaway,
3. Poloidal flux required for an e-fold, and
4. Decay rate of relativistic electrons.

Number of Seed Electrons

Need seed electrons above critical kinetic energy for runaway, K_r, to begin runaway process. (*Need experiments to study number*)

Most credible source is the pre-thermal-quench Maxwellian tail

$$\mathcal{F}_{tail}^{(Max)}(\epsilon) = \frac{2\sqrt{\epsilon}}{\sqrt{\pi}} e^{-\epsilon}, \text{ where } \epsilon \equiv \frac{mv^2}{2T}.$$

When electrons with $\epsilon < \epsilon_f \approx 9.5$ can runaway with

$$\mathcal{F}_{tail}^{(Max)}(\epsilon_f) \equiv \frac{j_{||}}{j_c}, \text{ where } j_c \equiv enc, \text{ so } \frac{j_{||}}{j_c} \approx 2\times10^{-4},$$

runaway is fast requiring only a tiny poloidal flux change,

$$\psi_{pa} \equiv \frac{mc}{e} 2\pi R \approx 0.064\text{V·s}.$$ Apparently seen on TFTR.

When $\mathcal{F}_{tail}^{(Max)}(K_r/T) \equiv \frac{j_{||}}{j_c} e^{-\sigma_s}$, σ_s e-folds required for runaway.

Kinetic Energy Required for Runaway

$$K_r > \frac{mc^2}{2}\frac{V_{ch}}{V_\ell} \quad \text{where } V_{ch} \equiv 2\pi R E_{ch} \approx 2.9\frac{n}{10^{20}/m^3}\text{V}$$

Pitch-angle scattering and radiation can increase K_r.

When K_r>20kev, two sources of runaways are eliminated:

(1) Tritium decay—max. electron energy is 18.6keV.

(2) Collision with an α particle—max. energy is $4\frac{m}{M_\alpha}K_\alpha \approx$ 2keV.

Poloidal Flux Required for an E-fold

$\psi_{efold} = \gamma_{ef}\psi_{pa}$; *simple theory gives* $\gamma_{ef} = 2ln\Lambda \approx 25.$

$$\psi_{pa} \equiv \frac{mc}{e}2\pi R \text{ and } \delta\left(\gamma\frac{v_{||}}{c}\right) = \frac{\delta\psi_p}{\psi_{pa}}$$

1. *Energy Distribution of Runaways*

Large-angle collisions add new runaways:

At the minimum energy for runaway.

At a rate proportional to the runaway number density $n_r(t)$.

The distribution function for relativistic runaway electrons is then

$$f = \frac{n_r(t)}{p_0 p^2}e^{-p/p_0}, \text{ where } p = \gamma mc \text{ and } p_0 \equiv \gamma_{ef}mc.$$

Average relativistic factor is $\bar{\gamma} = \gamma_{ef}$; effects at $\gamma \gg \gamma_{ef}$ irrelevant.

2. *Energy in Runaways*

Energy in relativistic electrons $W_r = (\bar{\gamma} - 1)I_r\psi_{pa} \ll \frac{1}{3}I\Psi_p$,
I_r runaway current; $\frac{1}{3}I\Psi_p$ is the energy in the poloidal magnetic field.

Change in poloidal magnetic energy as $I_r \to I$ given by

$$\delta\left(\tfrac{1}{3}I\Psi_p\right) \approx \tfrac{2}{3}I\delta\Psi_p \text{ and } \delta\Psi_p = -\sigma_s\gamma_{ef}\psi_{pa}.$$

Only $1/\sigma_s$ fraction of the poloidal field energy goes to the relativistic electrons; the rest goes to Ohmic dissipation.

3. *Maximum Number of E-Folds σ_{max}*

$$\sigma_{max} = \frac{\Psi_p}{\psi_{e-fold}} = \frac{1}{\gamma_{ef}}\frac{\Psi_p}{\psi_{pa}}.$$

Simple theory gives $\gamma_{ef} = 2ln\Lambda \approx 25$ and $\sigma_{max} \approx 40$.

For a Maxwellian seed need $\epsilon < \epsilon_{max} = \epsilon_f + \sigma_{max} \approx 53$.

4. *Multiple Runaway Strikes during One Disruption*

When the required $\epsilon \equiv mv^2/2T$ for runaway is $\ll \epsilon_{max}$, only a small fraction of the poloidal flux $\Psi_p \approx 70\text{V}$·s is lost in a single acceleration. If 90% of the relativistic electrons are lost in a single strike, only 2.3 e-folds are need to give another similar strike.

5. *Calculations of γ_{ef}*

In standard theory $\gamma_{ef} \propto 1/K_r$, with K_r the runaway kinetic energy.

Since $\sigma_{max} \propto 1/\gamma_{ef}$, seriousness of runaway is strongly dependent on γ_{ef}.

Existing codes could give a more accurate γ_{ef}, but the avalanche formula requires modification for a reliable value.

Decay Rate of Relativistic Electrons

Relativistic currents decay by the loss of relativistic electrons.

For the current to decay need $V_\ell < V_s$, where the loop voltage required to sustain a relativistic current satisfies $V_s \geq V_{ch}$.
Inequality because Connor-Hastie voltage omits some dissipative effects.

When $V_s = V_{ch}$, the decay time is $\tau_{decay} \approx 24s\left(\frac{10^{20}/m^3}{n}\right)$.

Importance of V_s is questionable for two reasons:

1. The ITER vertical field system appears inadequate, so dissipation must be fast compared to 150ms to avoid drift into the wall.

2. The evolving profile of the relativistic current must remain tearing stable to avoid loss of magnetic surfaces.

May preclude mitigation of relativistic currents by massive gas or shattered pellet injection due to magnetic surface breakup.

Discussion

A strong relativistic electron current striking the walls more than one in a thousand shots would probably prevent ITER from achieving its mission.

Massive gas injection and shattered pellets rely on magnetic surface breakup to spread effect of impurities, which may preclude use for mitigation. Success for avoidance depends on dissipation of non-intercepting flux tubes before surfaces re-form.

Theory and simulation using physics validated in experiments could advance what a practical mitigation system would look like.

Two possibilities

A faster and more flexible pellet injector

Passively induced non-axisymmetric currents in chamber walls.