Runaway Mitigation Issues on ITER

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If the ITER chamber walls were struck by relativistic electrons carrying a current comparable to the net plasma current, the machine could be out of commission for many months.

Shortest credible time between such events must be at least years for a practical research program on ITER (*operability issue*).

Two points: ***(1) Existing physics brings into question ITER operability with favored mitigation design. (2) Rapid progress could be made with a focused research program.***

Plan of Talk

Slides 3-7:	Physics that defines runaway issues
Slide 8:	Scenario under which mitigation is required *Loss of position control -> halo & runaway damage*
Slide 9:	Clarifications of physics achievable near term
Slides 10-11:	Mitigation with reduced sensitivity to physics
Slide 12:	Strategy for dealing with mitigation issue

ITER Organization recognizes importance of runaway issue and encourages research, workshops, ITPA activities, etc.

Nevertheless, a more focused program appears required.

Two Quantities Establish Runaway Time Scales on ITER

1. Poloidal flux between magnetic axis and wall $\Psi_p < 100\text{V}\cdot\text{s}$.

2. Loop voltage needed to balance drag on relativistic electrons by background electrons of density n_b

$$V_{ch} \approx 3\frac{n_b}{10^{20}/\text{m}^3}\ \text{Volts}$$ *when* $Z=1$*; standardly* $n_b \sim 10^{20}/\text{m}^3$.

When the loop voltage is V_ℓ, electrons with a kinetic energy

$$K_r > \tfrac{1}{2}m_e c^2 \frac{V_{ch}}{V_\ell}$$

can accelerate (*or runaway*) to a relativistic energy.

Time required to remove the poloidal flux is $\dfrac{\Psi_p}{V_\ell}$.

~30s required to ensure no drive of relativistic electrons.
*Removal on wall time, 200*ms*, allows runaway at* $K_r \sim 1.5$kev.

Tokamak Plasmas can Drift into Wall on Wall Time

To prevent this, plasma must be cooled to remove Ψ_p quickly.

$$V_\ell = 2\pi R\eta j \approx 3\times10^4 \frac{Z_{eff}}{T^{3/2}} j$$ *T* in eV and *j* in MA/m^2. ITER has $j{\sim}1$.

$V_\ell \sim 500\,\text{Volts}$ for flux removal on wall time; $T{\sim}15\ Z_{eff}^{2/3}$ eV.

When $T_{cold}<K_r/53{\sim}30$eV, a Maxwellian has less than one electron above energy required for runaway (~ *e^{53} electrons in ITER*).

Assumes K_r=1.5keV, but $K_r \propto n_b$ and a function of Z at a given V_ℓ.

When K_r>20keV, remaining hot-Maxwellian tail essentially only source for runaway seed.

The hot-Maxwellian-tail source requires very rapid cooling.

Maximum Cooling Time to have a Hot-Maxwellian-Tail

Mildly relativistic electrons slow down in a time

$$\tau_{ch} \equiv \frac{m_e c}{eE_{ch}} \approx 23\text{ms}\frac{10^{20}/\text{m}^3}{n_b}.$$

Electrons of energy K_q survive collisional cooling for a time τ_q,

$$K_q = \left(\frac{3\tau_q}{2^{3/2}\tau_{ch}}\right)^{3/2} m_e c^2.$$

Fraction of electrons in hot Maxwellian above K_q is

$$f_{tail} = \frac{2}{\pi}\sqrt{\frac{K_q}{T_{hot}}}\exp\left(-\frac{K_q}{T_{hot}}\right).$$

Nature of runaway depends on size of f_{tail}.

Dependence of Nature of runaway on size of f_{tail}

1. When f_{tail}>e^{-9} enough tail electrons remain to carry the full current after acceleration to a relativistic energy. (*Seen on TFTR.)*
   a. Requires surviving tail energy K_q satisfy $K_q<10T_{hot}$.
   b. A tiny poloidal flux change required for acceleration; P_φ conservation implies

$$(\delta\psi_p)_{acc} = (\gamma-1)\frac{2\pi m_e cR}{e} \approx 0.07(\gamma-1)\mathrm{Volt}\cdot\mathrm{sec}.$$

2. When $f_{tail} = e^{-(9+\sigma_s)}$, the number of runaway electrons must e-fold σ_s times to transfer current to relativistic electrons.

Poloidal flux change for an e-fold by avalanche mechanism

$$\psi_{e-fold} > \psi_c \equiv 4\pi R(m_e c/e)\ln(\Lambda) \approx 2.3\mathrm{Volt}\cdot\mathrm{sec}.$$

Required time is $\sigma_s\psi_{e-fold}/V_\ell$ assuming $\sigma_s\psi_{e-fold} < \Psi_p < 100\mathrm{Volt}\cdot\mathrm{sec}$

Enhanced Loss by Broken Magnetic Surfaces

High-energy electrons are rapidly lost when they lie on magnetic field lines that reach the chamber walls—even stochastically.

A rapid loss, ~10ms, of electron temperature is generally assumed to be caused by the loss of toroidally confining surfaces.

The loss of toroidally confining magnetic surfaces does cause rapid cooling, but need not prevent runaway if a magnetic island remains that contains a toroidal flux >3% of the total. Energetic trapped electrons may also survive if surfaces close quickly.

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Large regions of stochastic magnetic field lines bounded from walls by a region of good surfaces is especially dangerous.

Relativistic electron loss is in pulses along narrow flux tubes.

More Often Than Once a Year

Axisymmetric Position Control may be Lost

Unless the plasma current decays more rapidly than edge plasma is scraped away, $dq_{edge}/dt>0$. The plasma will become so kink unstable when $q_{edge}\sim 2$ that a strong halo current will arise.

What strategy does ITER have for dealing with such events?

To avoid damage from halo current, ITER plans a rapid plasma cooling over 10's ms to ensure $dq_{edge}/dt>0$.

Such a rapid cooling may well transfer current to relativistic electrons, which would stop the decay of the plasma current.

Would make damage from both the halo and relativistic currents likely.

What Near Term Physics Clarifications Are Possible?

1. Theoretical determination of $K_r(n_b, Z, V_\ell)$.

2. Experimental limits on $f_{tail} = e^{-(9+\sigma_s)}$ after thermal quenches.

3. Simulation of resistivity increase and acceleration of tail electrons when plasma is rapidly cooled by either radiation or loss of toroidally confining surfaces. Radial dependence is important.

4. Theoretical determination of $\psi_{e\text{-}fold}$, including Z dependence.

Given a plasma state, theory can simulate runaway-current growth; existing experiments cannot. Existing experiments can define plausible plasma states; theory cannot. Both needed.

Is a More Flexible Mitigation System Required?

Gas injection may not raise the density in the plasma core.

A shattered pellet injector (*presently favored*) could be designed to reach the core of a given plasma but is not flexible.

Both gas injection and standard pellet injection are slow, ~25ms.

Runaway electrons naturally arise or evolve toward the magnetic field lines that have low density, $V_{ch} \propto n_b$.

Density must be high at magnetic axis or mitigation is ineffective.

Poloidal fan of pellets may be necessary with opposite side armored.

Multiple injections may be required to raise *Z* but not to have too much radiation.

Unless Operability is assured by 2018 Design Review

Engineering will be needed to determine whether modifications to reduce uncertainties are more than a just cost issue.

1. What time is required to develop injectors with faster pellets?

2. Is space available for multiple injectors for $Z(t)$ control?

3. Can different size and composition pellets be used for different plasma conditions?

4. What is the strategy for ensuring the magnetic axis is hit?

5. Could the induced wall currents be used to ensure no confining toroidal magnetic surfaces or islands remain?

Strategy for Addressing Runaway Issues

1. Runaways are fundamentally just a tokamak issue.

   In stellarators I_p is generally too small for runaway issues, and halo currents due to loss of position control are not possible.

   Nevertheless, an inoperable ITER becomes a fusion issue.

2. The mitigation system cannot be experimentally validated because of danger to machine--theory and experiment required.
   a. Theory and codes exist that have predictive capability.
      Conservative theory ignores microinstabilities.
      They appear unlikely to ease mitigation requirements.
   b. Primary experimental issue is pre-runaway plasma state.

3. Rapid progress on ensuring the operability of ITER could be made with a focused program (*not just workshops*) led by (a) the ITER Organization, (b) DoE-FES, or (c) a major laboratory.