Protection of ITER from Relativistic-Electron Damage

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Tokamak Current Spikes and the Transfer of Current to Relativistic Electrons, submitted for publication.
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Incidents involving relativistic electrons require months to repair.

For ITER to achieve its mission, such incidents must be separated by years (thousands of pulses or *99.9% reliability*).

Existing disruption mitigation plan is based on shattered pellets, but they may do little to avoid relativistic-electron incidents.

I. Basic issues

1. Pellets require about 20 ms to reach plasma. Transfer of current to relativistic electrons can occur in milliseconds after a thermal quench.

Is a 20 ms warning of thermal quenches so assured to make relativistic electron incidents after prediction failures acceptable?

2. Seed electrons from tritium decay add significantly to the difficulty of avoiding relativistic electron incidents.

Absence of runaway incidents in the non-nuclear phase is not an assurance for the nuclear phase.

What are the implications? Major modifications to ITER are extremely difficult after the beginning of nuclear phase.

Faster response that 10 ms requires fundamental design changes.

3. Current spike during the thermal quench is indicative of a fast opening of magnetic surfaces, ~1 ms.

a. When all confining magnetic surfaces are broken for a time τ_{op}, then only trapped electrons from pre-quench Maxwellian can contribute to the seed electrons in non-nuclear phase.

In nuclear phase, electrons from tritium decay also contribute.

When $\tau_{op} \lesssim 1$ ms, essentially full plasma current is transferred.

When $\tau_{op} \gtrsim 10$ ms in non-nuclear and $\tau_{op} \gtrsim 75$ ms in nuclear phase current is not transferred to relativistic electrons.

b. When only a fraction of the magnetic surfaces is broken, skin currents naturally arise that increase the accelerating voltage, probably by an order of magnitude.

Raises critical density for blocking runaway by ~10.

4. How impurities reach center is obscure.

Bohm diffusion is too slow.

Speed of thermal quench, $\lesssim 1$ ms even in plasma center, appears to require impurity radiation. Both Bohm diffusion and electron heat transport along open magnetic field lines are too slow at observed T_e's.

5. Does pellet injection need to reach plasma center?

Without impurities in center:

a. No blocking of runaways by impurities there.

b. Obtain a peculiar temperature profile.

6. Can a relativistic-electron current be benignly terminated?

a. Requires either axisymmetric control be maintained or the termination occur in less than 150 ms, which requires a few-hundred-fold increase in the electron density along every magnetic field line.

Control is difficult when current is low but still dangerous.

b. Requires current profile remain stable to MHD modes, which is difficult when safety factor $q \lesssim 10$.

II. Exponential sensitivities to I_{10}, τ_a, and τ_{op}

What might appear to be minor changes in assumptions can change the relativistic-electron current from nil to 15 MA.

1. During the current quench, the number of energetic electrons is amplified by the factor

$\mathbf{10^{|\delta I_p/I_{10}|}}$, where I_{10}~1 MA in common approximations.

A factor of two uncertainty in I_{10} can give a factor of ten-million uncertainty in the number of seed electrons required for amplification.

$I_{10} \gtrsim 2$ MA would eliminate tritium decay as an important seed.

2. Seed from pre-thermal-quench passing electrons depends exponentially on $\tau_a^{2/3}$ in regions confined by a magnetic surface.

τ_a is the time after start of thermal quench for the loop voltage to surpass the Connor-Hastie value, which is when the electric field acceleration surpasses the Coulomb drag.

$\tau_a \lesssim 1$ ms implies essentially the full 15 MA transferred to runaways.
$\tau_a \gtrsim 10$ ms implies no important seed from this source.

3. Seed from pre-thermal-quench trapped electrons depends exponentially on $\tau_{op}^{2/3}$ in regions of open field lines

τ_{op} is the time after start of thermal quench where magnetic field lines are open--a region not bounded by a magnetic surface.

$\tau_{op} \lesssim 1$ ms implies essentially the full 15 MA transferred to runaways.
$\tau_{op} \gtrsim 10$ ms implies no important seed from this source.

4. During nuclear phase, even if all energetic electrons from the pre-thermal quench are lost, **tritium decay can give a relativistic electron current density that increases in regions bounded by magnetic surfaces**

$$\boldsymbol{j_{rel} = ec\dot{n}_t\tau_{ef}\, e^{t/\tau_{ef}}} \;,$$

where $\dot{n}_t \equiv n_t/\tau_{decay}$ rate of tritium decay, and τ_{ef} is the time for an e-fold in the number of energetic electrons.

Can result in ~7 MA of relativistic electrons, but would give a negligible current if $I_{10} \gtrsim 2\ MA$ or if all field lines are open until at least half of the plasma current is dissipated.

III. Magnetic Surface Breakup

Fundamentally changes the processes of electron runaway.

The current spike and the sudden inductance drop, ~1 ms, during thermal quenches implies current profile flattening by a fast magnetic reconnection. A large fraction of the magnetic surfaces is broken.

Fast magnetic reconnection occurs on a time scale set by Alfvénic not resistive effects and requires spatial and temporal resolutions far beyond those of existing disruption simulations.

Without resistive effects, magnetic helicity content $-2\int \psi_p d\psi_t$ is conserved. The two-time-scale relaxation naturally gives skin currents, which makes blocking electron runaway far more difficult.

$\vec{E}\cdot\vec{B} = \eta\vec{j}\cdot\vec{B} - \vec{\nabla}\cdot\left(\lambda\vec{\nabla}(j_{||}/B)\right)$ allows fast modelling of two time-scale evolution. Much could be learned from existing experiments.

IV. Discussion

The report on the March 2017 ITER workshop on the disruption mitigation system (DMS) said:

"*A fully functional and effective DMS is essential for ITER to achieve its mission…The participants to this meeting, 24 external experts from all Members' fusion communities and several senior ITER scientists and engineers, emphatically agree that immediate decisive action must be taken to directly support research into solutions to outstanding critical issues relating to the specification and performance of the DMS. The consensus is that significant uncertainties exist, in particular, as to whether the present baseline disruption mitigation system will offer sufficient protection to ITER from relativistic electron impacts*."

To achieve the required 99.9% reliability, central issues must be defined and addressed by theory, experiments, and engineering.