Runaway Electron
Confinement in MHD
Disruption Mitigation
Simulations

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Motivation

- Suppression of runaway electron (RE) avalanche during an ITER current quench will require that one of two conditions are met:
  1) Sufficient electron density to achieve $E/E_{\text{crit}} < 1$ (where $E_{\text{crit}} \approx 0.12 n_e^{20}$)
  Or
  2) Short enough RE confinement time such that secondary REs are not produced in great enough numbers to sustain an avalanche

- Condition 2) might be met by “natural” disruption-induced MHD turbulence, or by the application of external perturbing fields
- DIII-D has performed disruption/RE experiments with injected Ar ice pellets both with and without applied I-Coil fields
- NIMROD simulations with atomic physics from KPRAD and single-particle orbit RE modeling examine both criteria under this scenario
DIII-D shows prompt loss of runaways to divertor, later losses to main chamber

- Runaways give gamma flashes ($\varepsilon > 0.5$ MeV) upon hitting wall.
- Strong prompt loss flash of REs lost into lower divertor at start of CQ.
- Weaker loss of REs into main chamber wall during CQ.
- Strong late loss flashes when RE beam drifts into wall at end of CQ.
Electron Single Particle Orbits in NIMROD

The fast electron orbit model is a diagnostic tool that runs concurrently with NIMROD to study runaway electron confinement

- A small set (presently hundreds) of electrons is initialized at random locations with specified energies, and the RE orbits are integrated as the magnetic and electric fields evolve in NIMROD
- The governing equations include curvature and grad-B drift, acceleration by the electric field, and slowing due to collisions, bremmstrahlung and synchrotron radiation
- The electrons are purely trace—they do not impact the NIMROD fields

The model does not include runaway generation

- Seed and avalanche terms are not included, the population of REs is fixed based in the (random) initial conditions

Model can tell us about: runaway confinement time, strike points of escaping electrons. The model cannot predict: total runaway current, energy distribution of REs
Equations

\[ dR = \frac{v_{\parallel}B_R}{B} \frac{dt}{dt} + \frac{1}{B^2} \left[ V_R \left( B_\phi^2 + B_Z^2 \right) - B_R \left( V_\phi B_\phi + V_Z B_Z \right) - \eta (J_\phi B_Z - J_Z B_\phi) \right] dt \]

\( E \times B \) drift

\[ dZ = \frac{v_{\parallel}B_Z}{B} \frac{dt}{dt} + \frac{20 kT_e}{eB} R \frac{1}{R} \frac{dt}{dt} + \frac{\gamma v_{\parallel}^2}{eB} R \frac{1}{dt} + \frac{1}{B^2} \left[ V_Z \left( B_R^2 + B_\phi^2 \right) - B_Z \left( V_R B_R + V_\phi B_\phi \right) - \eta (J_R B_\phi - J_\phi B_R) \right] dt \]

\( E \times B \) drift

\[ d\phi = \frac{v_{\parallel}B_\phi}{RB} \frac{dt}{dt} - \frac{1}{RB^2} \left[ V_\phi \left( B_R^2 + B_Z^2 \right) - B_\phi \left( V_R B_R + V_Z B_Z \right) + \eta (J_Z B_R - J_R B_Z) \right] dt \]

\( E \times B \) drift

\[ dv_{\parallel} = - \frac{enJ_{\parallel}}{m_e \gamma^3} \frac{dt}{dt} + \frac{e^4 \ln A}{4\pi \epsilon_0 m_e^2} n_e (Z_{\text{eff}} + 1 + \gamma) \frac{1}{v_{\parallel}^2} \frac{1}{\gamma^4} \frac{dt}{dt} - \frac{e^2}{6\pi \epsilon_0 m_e e^3 \gamma^3} v_{\parallel}^3 \gamma \left( \frac{1}{R_0^2} + \frac{19.4 e^2 B^2 v_{\parallel}^2}{m_e v_{\parallel}^4} \right) dt + \frac{n_e e^4 (Z_{\text{eff}} + 1)}{548 \pi^2 \epsilon_0^2 m_e^2 c^2 \gamma^2} \left( \ln (2\gamma) - \frac{1}{3} \right) dt \]

Electric field
Collisional slowing
Synchrotron
Bremsstrahlung
Large drift displacement at high energy can improve confinement

Curvature drift can improve confinement on stochastic fields, but also reduce confinement on field lines that approach the boundary.

Electrons with $\gamma = 1/\sqrt{1-(v/c)^2}$

~20 (10 MeV) have curvature drift displacement of a few cm

With drift displacement ~ perturbation width, RE can appear well confined.
In DIII-D simulations, impurity delivery is instantaneous and uniform.

Simulation is initiated with large neutral density of Ar everywhere in the plasma:

- “Instantaneous delivery” creates extremely fast (unphysical) thermal quench and very high radiated power for a very short time.
- Following a real DIII-D TQ, impurities are well mixed and plasma is cooled everywhere.
- Following simulated (super fast) TQ, impurities are well mixed and plasma is cooled everywhere.

**Cold, Low S CQ simulation commences on physical time scales**
Current quench simulations are run with odd, even, and no I-Coil fields

- Applied fields are $n=3$ vacuum fields for both even and odd parity I-Coil currents
- Even parity has strong resonant components, odd parity is mostly non-resonant
Simulations are free-boundary, but domain does not extend to the DIII-D wall

Boundary extends beyond LCFS, but must be kept inside I-Coil location

Resistivity is **Spitzer** (cold CQ plasma requires no artificial enhancement):

\[ \eta = 13.7 \mu_0 Z_{\text{eff}} (10/T_e)^{3/2} \text{ Ohm-m} \]

Heat transport is approximately Braginskii:

\[ \chi_\perp = 0.2(40/T_i)^{1/2}(1/B^2) \text{ m/s} \]

\[ \chi_\parallel = 2 \times 10^6 (T_e/40)^{5/2} \text{ m/s} \]
“Ar pellet” simulations show MHD event part way into the current quench

1) Ultra-fast (unphysical) TQ
2) Early CQ ($P_{rad} = P_{ohmic}$)
3) MHD phase
4) Late CQ phase
Total radiated energy in simulation agrees well with experiment.
Key Result: NIMROD simulations find that \( n=3 \) fields enhance RE confinement

In each case, 239 fast electrons were launched from identical starting points at \( t=0 \). Prompt loss to divertor occurs during MHD phase. \( \text{Late loss is to main chamber} \).

Confinement is better with even or odd I-Coil fields.
I-Coil fields alter details of the MHD crash, amplitudes are quite similar
Without I-Coils, core flux surfaces are more thoroughly destroyed by MHD.

No I-Coils

Even I-Coils

Original LCFS
Without I-Coils, core flux surfaces are more thoroughly destroyed by MHD.
As flux surfaces begin to re-heal, core of well confined REs remains in I-Coil case

\[ \gamma = \frac{1}{\sqrt{1 - \left(\frac{v}{c}\right)^2}} \]

\[ \gamma = 45 \Rightarrow 25 \text{ MeV (DIII-D measured energy)} \]
Late in time, high energy REs become deconfined due to large drift displacement.
Considerably more density would be required for collisional RE avalanche suppression.

Early CQ

Time = 0.377 ms

Contours of $E/E_{\text{crit}}$

Late CQ

Time = 0.927 ms
Conclusions

1) The direct impact of RMP fields from the DIII-D I-Coils on RE confinement during the current quench is negligible, but ...

2) The details of the MHD crash are altered by the presence of perturbing n=3 fields

3) The amplitude of the fluctuating fields alone is not a good measure of RE confinement

4) In the case where n=2 was the dominant mode (no I-Coils) the destruction of the flux surfaces was maximum

5) I-Coil fields with n=3 symmetry enhance RE confinement during current quench in NIMROD. Maybe n=2 perturbations?

6) Findings may not contradict DIII-D results, which show loss of seed population before current quench
Possible Model Improvements

1) Avalanching: probably the easiest next step using simple expression to generate secondary electrons as the simulations progresses:

\[
\frac{dn_{sr}}{dt} = \frac{n_r eEc}{2m_0 c^2 \ln \Lambda (2 + Z_{eff})/3}
\]

Could produce the correct exponential distribution with high energy REs gradually lost, while bulk remains confined.

2) Seed terms are harder: Dreicer appears not to be a plausible mechanism for primaries on DIII-D. Might be hot-tail, but still unclear. Would need to get cooling rate correct for hot-tail.

3) Modeling the runaway beam in NIMROD: Probably needed to understand upward drift, but seems difficult. No plans on this.