MHD Simulations of Disruption Mitigation on Alcator C-Mod and DIII-D

By
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Motivation

• Disruption mitigation is a serious problem for ITER, and is being investigated on present tokamaks. Runaway electron avalanching is a major concern given exponential scaling with plasma current.

• Massive gas injection (MGI) is one approach that has been studied on Alcator C-Mod and DIII-D

• MGI is a 3D process in which MHD plays an important role—physics of MGI needs to be better understood

• A model capable of extrapolating MGI results to ITER must be 3D and accurately account for both MHD and atomic physics—an extended version of NIMROD has been developed for this purpose

• Validation of the code against present experiments, along with improved understanding of results is the focus in the near term
Outline

1) The physics of MGI: experimental observations and present understanding

2) The code: Atomic physics package for impurity modeling has been added to NIMROD
   - Equations, neutral source model, adjustment of time scales

3) Qualitative comparison: MGI sequence of events is captured by simulations

4) Quantitative comparisons:
   - Thermal quench time agrees w/ C-Mod for neon jets
   - Helium jet simulations require background impurities

5) Conclusion, Future work
DIII-D Discharge 122516 Shows MGI Sequence of Events

1) Valve opens and gas travels down tube
2) Gas reaches plasma, edge begins to cool, current profile contracts
3) $m=2$ and $m=1$ modes are destabilized, flux surfaces are destroyed
4) Core thermal quench due to enhanced thermal transport and/or impurity mixing
5) Current quench

Simulations of stages 2-4 are presented
Modeling of Impurity Species is Added to NIMROD

NIMROD is a 3D MHD code → nimrodteam.org

Atomic physics package computes ionization, recombination, radiation for all charge states of impurity species– source terms added to MHD equations

Energy

\[ n_e \frac{dT_e}{dt} = (\gamma - 1)[n_e T_e \nabla \cdot \mathbf{V} + \mathbf{V} \cdot \mathbf{q}_e - Q_{\text{loss}}] \]

\( Q_{\text{loss}} \) includes ionization, line radiation, bremsstrahlung, and recombination losses, as well as dilution cooling

Heat Flux Vector

\[ q = -n[\chi_{||} \hat{b} \hat{b} + \chi_{\perp} (I - \hat{b} \hat{b})] \cdot \nabla T \]

\( \chi_{\perp} \sim 1 \text{ m}^2/\text{s} ; \chi_{||} \sim 10^{10} \text{ m}^2/\text{s} \)

Ohm’s Law

\[ \mathbf{E} + \mathbf{V} \times \mathbf{B} = \eta \mathbf{J} \]

\( \eta \) proportional to local \( Z_{\text{eff}} \) as well as \( T_e^{-3/2} \)

Momentum

\[ \rho \frac{d\mathbf{V}}{dt} = -\nabla p + \mathbf{J} \times \mathbf{B} + \nabla \cdot \mu_p \nabla \mathbf{V} \]

Pressure and mass density include impurity contribution
Separate Evolution of Three Densities Allows Impurity Mixing

Electron Continuity

$$\frac{dn_e}{dt} + n_e \nabla \cdot \vec{V} = \nabla \cdot D \nabla n_e + S_{\text{ion/rec}}$$

Addition of source term due to ionization/recombination

Deuterium Ion Continuity

$$\frac{dn_i}{dt} + n_i \nabla \cdot \vec{V} = \nabla \cdot D \nabla n_i + S_{\text{ion/3-body}}$$

Includes term for ionization and 3-body recombination (becomes significant at T~1eV)

Impurity Ion Continuity

$$\frac{dn_z}{dt} + n_z \nabla \cdot \vec{V} = \nabla \cdot D \nabla n_z + [S_{\text{ion/rec}}]$$

Source term is not part of the NIMROD advance– individual charge state populations are updated within atomic physics subroutines

Quasi-Neutrality

$$n_e = n_i + \langle Z \rangle n_z$$

After advancing 3 densities, specifies required $\langle Z \rangle$ for charge state distribution
Approximate Model for Neutral Gas Injection Neglects Jet Asymmetry for Simplicity

- Model assumes gas injection is poloidally and toroidally symmetric (although 3D capability exists)

- Assumed initial radial injection depth is 1 cm (limited by grid resolution); as edge temperature falls below species first ionization energy, neutral deposition extends into that region

- Total impurity injection rate (vs. time) from gas dynamic code is divided by volume of the injection region to get neutral density deposition rate
Simulation Time Scales Are Artifically Reduced for Computational Expediency

- Resistivity is enhanced by a large factor, E (100-900)

- **Assumption:** During the thermal quench phase of the mitigated disruptions, the important processes are **heat loss** by radiation and transport and **reconnection**

- Reconnection scales roughly as \( \eta^{1/2} (\sim E^{1/2}) \)

- Therefore: Other rates including **atomic physics rates**, **transport coefficients**, **gas injection rates**, are increased by \( E^{1/2} \)

- Resistivity in Ohmic heating term is only enhanced by \( E^{1/2} \) to achieve correct balance between radiation, Ohmic heating. Some magnetic energy vanishes.

- When compared with the experiment, **time base** is multiplied by \( E^{1/2} \), radiated power is reduced by \( E^{1/2} \)
Simulated Lundquist Numbers Are Several Orders of Magnitude From ITER

<table>
<thead>
<tr>
<th></th>
<th>Lundquist number ( S \sim RBT_e^{3/2}n_e^{-1/2} )</th>
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</thead>
<tbody>
<tr>
<td><strong>ITER</strong></td>
<td>( \sim 10^{10} )</td>
</tr>
<tr>
<td></td>
<td>((R=6.2 \text{ m}, B=5.3 \text{ T}, T_e=15 \text{ keV}, n_e=10^{20}))</td>
</tr>
<tr>
<td><strong>DIII-D</strong></td>
<td>( \sim 10^8 )</td>
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<tr>
<td></td>
<td>((R=1.7 \text{ m}, B=2.1 \text{ T}, T_e=3.5 \text{ keV}, n_e=9\times10^{19}))</td>
</tr>
<tr>
<td><strong>Alcator C-Mod</strong></td>
<td>( \sim 10^7 )</td>
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<tr>
<td></td>
<td>((R=0.6 \text{ m}, B=5.2 \text{ T}, T_e=2 \text{ keV}, n_e=2\times10^{20}))</td>
</tr>
<tr>
<td><strong>NIMROD</strong></td>
<td>(5\times10^4 - 2\times10^5)</td>
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</tbody>
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Each simulation takes \( \sim 4 \) days on 96 procs on Bassi (NERSC)

\[ S \sim 1/E \]
C-mod Neon Jet Simulation Shows Experimental Sequence of Events

NIMROD results:
- Inward propagating cold front to $r/a \sim 0.6$ followed by sudden core $T_e$ collapse
- Core thermal quench happens in $\sim 0.15$ ms

Experimental results:
- Penetration of cold front before thermal quench is slightly shallower
- C-Mod core thermal collapse $\sim 0.2$ ms

Simulation with $E=400$

$(S_{C-Mod} = 2 \times 10^7, S_{sim} = 5 \times 10^4)$
Large Pulse of Radiated Power Corresponds to Thermal Quench Onset

- Current profile contracts as plasma edge cools
- Following thermal quench, peak current density is twice initial value
- Radiated power remains low as cold front propagates in plasma edge
- ~GW radiated power when core temperature suddenly collapses
Thermal Quench at 1.5 ms Corresponds to Destruction of Flux Surfaces

Parallel thermal transport from core to radiating edge drops core temperature rapidly

- \( t = 0.8 \text{ ms} \)
- \( t = 1.47 \text{ ms} \)
- \( t = 1.62 \text{ ms} \)

Flux surfaces are completely destroyed in this case; other simulations have shown good flux surfaces remaining inside \( q=1 \)

Scaling of fluctuations with \( S \) will be important
Simulation’s Large Edge Density is Not Measured by C-Mod Thomson Scattering

NIMROD results:
- Large increase in edge density before thermal quench, no significant impurity mixing
- Small increase in core density after thermal quench

Experimental results:
- No edge density increase before quench
- Moderate core density increase after quench

\[ \Delta t_{ec} = -27.3 \text{ ms} \]
\[ \Delta t_{ec} = 0.4 \text{ ms} \]
\[ \Delta t_{ec} = 0.8 \text{ ms} \]
\[ \Delta t_{ec} = 1.1 \text{ ms} \]

\( t = 0 \text{ ms} \)
\( t = 0.4 \text{ ms} \)
\( t = 0.8 \text{ ms} \)
\( t = 1.47 \text{ ms} \)
\( t = 1.62 \text{ ms} \)

⇒ Difference could be ionization fraction, confinement, gas injection rate or distribution
Runaway Electron Avalanching Criterion Is Satisfied in Large Regions of the Plasma

- Ratio of electron density (free + bound) to critical density needed to stop runaway avalanching. (color scale is cut off at 1.0; \( n/n_{\text{crit}} < 1 \Rightarrow \text{avalanching} \))

\[ n/n_{\text{crit}} \approx \frac{0.12}{E(V/m)} \]

- Regions of runaway electron avalanching

- New runaway electron diagnostic on DIII-D will allow comparison

* ITER Physics Basis, Chapter 3, (pg. 2346)
Thermal Quench Onset Time Agrees With Data for C-mod Neon Simulations

Δt (ms) = thermal quench time – edge cooling start time

NIMROD: C-Mod, Neon E=400
Thermal Quench Onset Time Agrees With Data for C-mod Neon Simulations

\[ \Delta t \text{ (ms)} \]

thermal quench time – edge cooling start time

NIMROD:
C-Mod, Neon
E=400
E=225
E=100

He, Ne, Ar, Kr

Atomic Mass

Alcator C-Mod
More Cases Required for Convergence of Onset Time With Rescaling Factor

$E = 100$

$E = 225$

$E = 400$

$S \sim \frac{1}{E}$
Pure Helium Jet Simulation Produces Very Long Thermal Quench Onset Time

- Onset time >7 ms, compare with experimental time of 2-2.5 ms
- Simulation does not include intrinsic (or sputtered) boron radiation
- Thermal quench also differs qualitatively

Simulation with $E=400$

(S$_{\text{C-Mod}}=2\times10^7$, $S_{\text{sim}}=5\times10^4$)

At 5.3 ms, stochastization of flux surfaces results in merely incremental increase in total radiated power

Larger radiated power spike associated with 1/1 convection of heat from core to edge
Background Impurity Radiation Can Be Significant for Helium Jet Experiments

- Identical helium simulation but with assumed constant boron density of $4 \times 10^{18}$/m$^3$
- Coronal boron cooling rates are assumed
- Thermal quench start time is shortened to 3.4 ms

Unlike pure helium, stochastization of flux surfaces occurs sooner, produces very large radiated power spike
Helium Simulations Will Require Accurate Boron Profile for Quantitative Comparison

$\Delta t$ (ms)

thermal quench time – edge cooling start time

Helium w/o Boron

Helium w/ Boron

NIMROD: C-Mod, Neon E=400 E=225 E=100

H He Ne Ar Kr

Atomic Mass

C-Mod data

III-D National Fusion Facility San Diego

Alcator C-Mod
Helium Simulations Will Require Accurate Boron Profile for Quantitative Comparison

\[ \Delta t \text{ (ms)} \]

thermal quench time – edge cooling start time

- C-Mod data
- DIII-D data

Helium w/o Boron

Helium w/ Boron

NIMROD:
- C-Mod, Neon
  - E=400
  - E=225
  - E=100

Atomic Mass

H  He  Ne  Ar  Kr
DIII-D Fast Radiated Power Measurement Allows Direct Comparison With NIMROD

- DIII-D helium jet radiated power measurements show slow rise, not constant low level then large spike
- Helium radiation dominates early on, carbon radiation dominates later in time
- NIMROD simulation has fast rise time for total $P_{rad}$ - may be due to toroidally, poloidally uniform gas injection
- Peak amplitude is comparable

Simulation with $E=900$

($S_{DIII-D}=9 \times 10^7$, $S_{sim}=1 \times 10^5$)
Conclusion

- Atomic physics package has been incorporated into NIMROD to simulate disruption mitigation techniques.

- Simulations reproduce the qualitative behavior of MGI experiments: jet cools edge, destabilizes MHD modes, rapid core thermal quench.

- Simulated and experimental density profile results must be reconciled.

- Thermal quench onset time at $E = 100-400$ approximately matches C-Mod experimental time for neon gas jet.

- Simulations with helium gas jets will require accurate background impurity profiles for better comparison with experiment.
ITER Predictability is the Ultimate Goal

- **Improvements to the Model**
  - better understanding of neutral fueling, localization of gas jet
  - Free boundary simulations (allows transport across separatrix)
  - More accurate background impurity profiles/modeling
  - Higher S, further exploration/validation of rescaling

- **Further benchmarking against DIII-D, including high Z gases**

- **Runaway electron analysis including seed terms, avalanching and confinement**

- **Other mitigation techniques: designer pellets, liquid jets, etc.**

- **ITER simulations of promising, well benchmarked techniques**