Runaway Electron Transport & Disruption Mitigation Optimization on Alcator C-Mod

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OUTLINE

I. Optimization of massive gas injection using mixed gasses.

II. Lower Hybrid seeding for runaway transport studies: Stochastic electron transport suppresses runaways in massive gas disruption mitigation
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I. Optimization of massive gas injection using mixed gasses.

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Disruption mitigation is a critical issue for ITER

- Damage to internal components can be much more severe than present devices due to its large size & energy density

- The ideal disruption mitigation system would
  1. Reduce thermal loading of wall materials below damage limits.
  2. Reduce EM forces, particularly poloidal halo currents.
  3. Avoid or eliminate runaway electrons.
  4. Have a sufficient response time to “catch” detected disruptions.
Using mixed gases in Massive Gas Injection (MGI) disruption mitigation is motivated by simple gas dynamics

- MGI relies on “overwhelming” the plasma with radiating noble gases, e.g. Argon
- Delivery: high pressure (~100 bar) gas reservoir opened, gas flows down pipe to plasma
  - ITER: reservoir is behind blanket shield module so ~5 m distance from the plasma.
- Gas moves as a supersonic shock down pipe
  - Particle delivery rate set by reservoir pressure, pipe length & gas sound speed.

ITER timescale with pure Argon
Using mixed gases in Massive Gas Injection (MGI) disruption mitigation is motivated by simple gas dynamics

- Gas moves as a supersonic shock down pipe
  - Particle delivery rate set by reservoir pressure, pipe length & gas sound speed.

- Mixed-gas strategy on C-Mod & ITER:
  - Use “fast” light gas as carrier (D₂ or He)
  - Minority high-Z radiating noble gas impurity (e.g. Argon)
  - Ensure maximum particle delivery in termination timescale.
  - Avoid early-stage argon “dribbling” which triggers start of termination.
Helium - Argon fraction controls gas sound speed $c_o \sim 1/M^{1/2}$
Gas transit time & edge plasma thermal collapse vary as expected
Helium - Argon mixtures have optimized disruption mitigation timing & effectiveness
0-D KPRAD atomic physics code predicts current quench resistivity vs. argon fraction

• KPRAD
  - He + Ar radiation & ionization balance
  - Particles delivered to plasma volume using shock model.
  - No free parameters

• At argon fraction >10% the argon dominates radiated power.
  - Argon primarily sets plasma resistivity --> effective halo current mitigation

![Current quench resistivity graph](image)
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I. Optimization of massive gas injection using mixed gasses.

II. Lower Hybrid fast electron seeding for runaway transport studies: Stochastic transport suppresses runaways.
Motivation: Runaway electron amplification poses a serious threat to in-vessel components of large-scale tokamaks like ITER

• In the current quench of a disruption or mitigated termination, the large parallel electric field leads to runaway amplification.

• Rosenbluth & Putvinski\(^1\): \(I_r > I_p/2 > 7\) MA in ITER.
  ➢ Electrons \(\sim 20\) MeV

• Severe damage to plasma-facing components when RE beam is eventually lost.

\[
\frac{I_{\text{runaway}}}{I_{\text{runaway},0}} \propto \exp(\gamma_r \cdot \Delta t) \sim \exp(I_p / I_A) \\
\sim \exp\left(\frac{I_{p,MA}}{0.5}\right) \sim \exp(30)
\]

Runaway current \(I_r / I_o\)

Electric Field \(E / E_c \propto \gamma_r\)

Runaway energy \(KE / m_o c^2\)

e-folding times \((\gamma_r \cdot \Delta t)\)
The puzzle: *Larger* amounts of impurity injection suppress runaways in mitigated terminations when comparing pellets to massive gas injection (MGI).

- MGI ~ x100 particles in pellets
  - Improved mitigation of thermal damage and EM forces *from higher resistivity*.
  - Electric field ~ $\eta j$ increased

- Large particle injection, but at least x10 below Connor-Hastie-Rosenbluth (CHR) collisional suppression limit\(^1\)
  - Gas injection to CHR limit could pose technical & operational issues in ITER.

- **Conclusion:** Transport *loss* mechanism for electrons must be enhanced.
CQL3D\(^1\) Fokker-Planck simulations:
Slideaway runaway production &
Stochastic losses effectively suppress runaway conversion.

- Rechester-Rosenbluth electron diffusion for fixed \(\delta B_r/B\).
- **Promising but many open questions**
  - Real B topology?
  - Generation of stochastic B?

\(^1\) R. Harvey, Phys. Plasmas 7 (2000) 4590
Present devices match ITER runaway growth rate  
BUT amplification gain is limited by small size

Runaway Electron rate equation

\[
\frac{\partial}{\partial t} I_{RE} = I_{RE, seed} \delta(t = 0) + I_{RE} \gamma_{Rosenbluth} - \frac{I_{RE}}{\tau_{RE}}
\]

\[ I_{RE} \text{ Not measured: low magnitude since } R_{Cmod} << R_{ITER} \]

\[ I_{RE, seed} \sim \frac{dT_e}{dt} \quad \text{“Slideaways” Not measured, hyper-sensitive to } dT/dt \]

\[ \gamma_{Rosenbluth} \sim \frac{E_{\parallel}}{E_c} \sim \frac{\eta j}{n_e} \quad \text{Measured. Typically match ITER} \]

\[ \tau_{RE}^{-1} \sim \left( \frac{\partial B_r}{B} \right) \quad \text{Stochastic losses (e.g. CQL3D) thought important, but cannot measure due to other unknowns in rate equation} \]
Exploiting a large initial suprathermal electron population from Lower Hybrid allows ITER relevant tests of runaway amplification and losses in Alcator C-Mod.

Runaway Electron rate equation

\[ \frac{\partial}{\partial t} I_{RE} = I_{RE,seed} \delta(t = 0) + I_{RE} \gamma_{Rosenbluth} - \frac{I_{RE}}{\tau_{RE}} \]

- \( I_{RE} \) Measured: \( I_{RE} \sim I_p \)
- \( I_{RE,seed} \equiv I_{LH} \) Set by LH fast electrons
- \( \gamma_{Rosenbluth} \sim \frac{E_{\parallel}}{E_c} \sim \frac{\eta j}{n_e} \) Measured. Can match ITER
- \( \tau_{RE}^{-1} \sim \left( \frac{\partial B_r}{B} \right) \) Stochastic (or other) loss mechanisms quantified and examined

Current Quench durations

- \( I_r \sim I_p \)
- Apply Lower Hybrid RF to target plasma to produce large seed suprathermal electrons
Target C-Mod plasmas with Lower Hybrid seeding of suprathermal electrons

- Diverted single-null plasma:
  - \( I_p = 1 \) MA, \( B = 5.4 \) T
  - Core density \( \sim 1.6 \times 10^{20} \) m\(^{-3}\)
  - L-mode

- Lower Hybrid parameters
  - 4.7 GHz
  - \( P \sim 0.4 \) MW
  - Phasing: \( n// \sim 2.3 \)

- Suprathermal electrons
  - \( I_s \sim 100 \) kA*
  - \( (KE)_{s,,//} \sim 150 \) keV

- Terminate with MGI: 85%He:15%Ar

**0-D analysis:** Confined LH suprathermals should amplify to large runaway fraction $I_r/I_p$ following MGI termination

- Electric field at start of Current Quench
  - $E_{//} \sim 100-200$ V/m
- Particle density at CQ:
  - Total electrons: $\sim 10^{22}$ m$^{-3}$ (100 x target)
- C-H-R critical electric field for runaways
  - $E_c \sim 10^{-21}$ $n_e \sim 10$ V/m $\ll E_{//}$
- **Threshold:** $m_o(u_{crit})^2 \sim 16$ keV
  - Therefore ALL 100 keV LH electrons should runaway if present through seeding.
- Rosenbluth growth rate: $\gamma_r \sim E/E_c \sim 3000$ s$^{-1}$

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**Example MGI termination w/o LH**

85%He:15%Ar

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- $I_p$ (MA)
- $n_e$ ($10^{20}$ m$^{-3}$)
- Central $T_e$ (keV)
- Electronic command to valve
- Pressure in pipe outside valve

$\Delta t$ (ms)
0-D analysis: Confined LH suprathermals should amplify to large runaway fraction $I_r / I_p$ following MGI termination

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- Expected current in runaways:
  - Acceleration: $0.1$ MA x $(500$ keV$/100$ keV)$^{1/2} \rightarrow 0.2$ MA
  - Amplification: $\sim e^{2-3} \rightarrow I_r \rightarrow 0.5$ MA
He-Ar MGI terminations: **Suprathermal LH electrons convert to runaways but are rapidly lost by end of thermal quench**

Without Lower Hybrid

- $I_p$ (MA)
- $n_e$ ($10^{20}$ m$^{-3}$)
- Pressurepipe (au)
- $T_{e,edge} \times 2$
- $T_{e,0}$ (keV)
- Hard X-ray & Gamma rate (au)
- Neutron rate ($10^{12}$ s$^{-1}$)
- Soft X-ray: Central Edge

With Lower Hybrid

- $P_{LH}$ (MW)
He-Ar MGI terminations: Suprathermal LH electrons convert to runaways but are rapidly lost by end of thermal quench.

Without Lower Hybrid

With Lower Hybrid

Non-thermal ECE emission
He-Ar MGI terminations: Suprathermal LH electrons convert to runaways but are rapidly lost by end of thermal quench.

**Without Lower Hybrid**
- Hard X-rays from \(~100\) keV electrons
- Neutron rate \((10^{12} \text{ s}^{-1})\)
- Soft X-ray: Central, Edge

**With Lower Hybrid**
- Hard X-rays increase in absence of LH (Saturated detector)
- Hard X-rays to zero in \(~0.2\) ms

\[ \gamma_r^{-1} \]
He-Ar MGI terminations: Suprathermal LH electrons convert to runaways but are rapidly lost by end of thermal quench

Relativistic electrons (>10 MeV) hitting onto Mo wall $\rightarrow$ Gammas > 10 MeV $\rightarrow$ Photo-neutrons

Montalbetti et al Phys Rev 91 (1953)

Neutron rate \(10^{12}\) s\(^{-1}\)

Soft X-ray: Central Edge

With Lower Hybrid

\(P_{\text{LH}}\) (MW)
He-Ar MGI terminations: Suprathermal LH electrons convert to runaways but are rapidly lost by end of thermal quench

Non-thermal Soft X-rays: Bremsstrahlung
He-Ar MGI terminations: **Suprathermal LH electrons convert to runaways but are rapidly lost by end of thermal quench**

**Conclusion:**
Relativistic electrons are being lost due to transport on timescales that “win” vs. amplification
Mitigation is effective because convected energy from central plasma is dissipated by radiation in the extremely cold and dense edge.

Resulting plasma is highly stochastic → runaway electron loss?

NIMROD simulations: Resistive 3-D MHD + Atomic physics used to examine electron transport in well-documented & repeatable C-Mod MGI terminations

Izzo, APS07
Electrons initiated across plasma cross-section at $E_{//} = 150$ keV.

Relevant relativistic effects included:

- Drifts, acceleration, radiation (synchotron & bremsstrahlung), slowing down

Electrons are considered lost to wall if they step across $r/a \sim 0.95$
NIMROD simulations show progression of Cooling $\rightarrow$ E field $\rightarrow$ e- runaways $\rightarrow$ stochastic transport loss

Electron mass / rest mass $\sim KE$

Toroidal electric field (V/m)

$\star$ fast electrons
NIMROD simulations show progression of Cooling → E field → e- runaways → stochastic transport loss
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NIMROD closely matches the timescales & dynamics of the electron acceleration & loss:
Avalanche growth rate << transport loss rate

C-Mod

Model

Target $T_{e,0}$

Central ECE ($\ell/3$)

Hard X-rays & Gammas
(scintillator)

Hard X-rays & Gammas
(Edge viewing HXR chords)

Neutron rate ($10^{12} \text{ s}^{-1}$)

Time after gas arrives at plasma (ms)

$T_e$ (r/a <0.25)

$N_{\text{fast electrons}}$

Synchrotron radiation (MW)

Bremsstrahlung radiation (kW)

Electron E>10 MeV loss rate
~ Photoneutron rate (au)

Avalanche gain only

Avalanche gain + transport losses

Time after gas arrives at plasma (ms)
NIMROD shows similar $\delta B_r/B$ threshold as CQL3D FP code for large stochastic losses & suppression of runaway growth

Model:
Radial profiles of $\delta B_r/B$

![Graph showing radial profiles of $\delta B_r/B$ with times after gas arrives at plasma marked as 1.60 ms, 1.56 ms, 1.47 ms, 0.80 ms, and 0.40 ms.]
LH seeding + MGI terminations + NIMROD provide an exciting new tool to study runaway electron transport

- Several open questions remain to understanding RE transport towards predictions for ITER
  - Why do circular, limited plasma more readily get RE tails?
    - Elongation? MHD evolution?
  - What is the critical level of impurities? Why do pellets produce RE tails?
    - Set by violence of MHD activity?
  - What happens in the current quench?
  - What is the relative importance of internally produced stochastic fields versus external fields produced by coils?
Summary: Mixed gases for mitigation

- Gas mixing of light carrier gases with radiating heavier impurities provides optimization of massive gas injection disruption mitigation
  - Should be exploited on ITER where gas transit distances are long.
Summary: Runaway electrons

- C-Mod Lower Hybrid seeding of suprathermal electrons followed by MGI terminations provides a new set of experimental and modeling tools to quantify the dynamics of stochastic transport for runaway electrons.
  - C-Mod experiments + NIMROD agree with CQL3D that rapid loss of the relativistic electrons due to stochastic transport at $\delta B_r/B \sim 10^{-3}$ effectively suppresses runaway growth.
  - It is not necessary to attain the Connor-Hastie-Rosenbluth collisional limit to suppress runaways.
  - 3-D non-ideal MHD (NIMROD) captures most termination & electron features
  - The evolving, robust MHD driven by massive edge radiation is in fact the same process that de-confines the electrons due to growing stochasticity.
    This links disruption mitigation effectiveness to runaway suppression.

- Further experimental & modeling scoping should lead to much better predictive capability for runaway electron suppression in ITER.
Extra Materials
We use the NIMRAD 3-D evolution of the B topology + trace electrons to study e transport in MGI termination with 100 kA LH

Initial 100 keV e- Relativistic e-

- Electrons are followed along B.
- Position, v, stepped across solutions.
- No radiation losses, etc.
- “Lost” when exceeds r/a = 0.95, i.e. BY TRANSPORT ONLY