DIII-D research in support of the ITER disruption mitigation system

by

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DIII-D program aims to produce critical knowledge for the design & operation of the ITER Disruption Mitigation System

- Establish physics & limitations of shattered pellet injection (SPI)
- Probe the mechanisms governing runaway electron (RE) evolution
- Develop new “inside-out” mitigation by core impurity deposition
DIII-D program aims to produce critical knowledge for the design & operation of the ITER DMS

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For several years, DIII-D has been only device able to test SPI, the baseline ITER DMS technology

- **Solid cryogenic impurity pellet shattered prior to entering plasma**
  1. Protects in-vessel components from a large solid pellet
  2. Improves assimilation due to increased surface area
  3. Provides faster response over long distances than massive gas injection (MGI)

- **DIII-D operates two SPI systems**
  - Toroidally separated by 120°

- **New SPI online 2018 (J-TEXT, JET)**

E.M. Hollmann et al., PoP 2015
Simultaneous injection of multiple SPI exhibits unexpected degradation in mitigation performance

- **ITER:** Multiple simultaneous SPI needed to reduce radiation asymmetries & provide massive D$_2$ input for RE suppression

- **DIII-D:** Simultaneous injection of two pellets (10 torr-L & 400 torr-L Ne) exhibits worse 0-D mitigation metrics than single 400 torr-L pellet

\[ f = \frac{W_{\text{rad,TQ}}}{W_{\text{th}}} \]

Arrival = Reaching plasma edge
Simultaneous injection of multiple SPI exhibits unexpected degradation in mitigation performance

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**Hypotheses**

1. Lighter/faster SPI hits $q=2$ first, initiates TQ (**easy fix**)
2. Dilution cooling reducing ablation (**not ITER problem**)
3. Impurities in multiple flux tubes initiate TQ faster than single flux tube (**basic physics problem**)
Simultaneous injection of multiple SPI exhibits unexpected degradation in mitigation performance

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DIII-D experiments planned in 2019 to test hypotheses.
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Two regimes used to study RE: Flattop "quiescent" runaway (QRE) & post-disruption RE plateau

**QRE**

- $I_p$ (MA)
- $\langle n_e \rangle$ ($10^{13} \text{ cm}^{-3}$)
- HXR (log10 au)

**RE Plateau**

- $I_p$ (MA)
- $T_e$ (keV)
- HXR (au)

C. Paz-Soldan et al., PoP 2014

E.M. Hollmann et al, NF 2017
Two regimes used to study RE: Flattop “quiescent” runaway (QRE) & post-disruption RE plateau

Strengths of using QRE to study RE physics:
1. All DIII-D profile diagnostics available
2. Slow evolution
3. Trace RE avoid signal saturation
Observed RE f(E) exhibit qualitative agreement on collisional & synchrotron effects with theoretical model

- Non-monotonic peak observed at predicted energy
- Peak moves to lower energy with increased density (collisionality)
- Increasing $B_T$ (synchrotron) suppresses high-energy RE

Model = 0-D Fokker-Planck + collisions & radiation
NO FREE PARAMETERS

C. Paz-Soldan et al, PoP 2018
C. Paz-Soldan et al, PRL 2017
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Significant quantitative discrepancy in high energy tail – possibly due to kinetic instabilities (later)

C. Paz-Soldan et al, PoP 2018
C. Paz-Soldan et al, PRL 2017
Anomalous behavior in the critical electric field ($E_{\text{crit}}$) for RE growth shows a strong energy dependence.

- Previous results (without energy resolution) found HXR decay at anomalously high $E/E_{\text{crit}}$.

- Energy-resolved measurements reveal $E/E_{\text{crit}}$ threshold decreasing with increasing RE energy.

- Extrapolated $E/E_{\text{crit}}$ threshold for 6MeV RE in good agreement with theory incorporating pitch angle scattering & synchrotron effects.  

\[ E/E_{\text{crit}} = 1 \]

\[ \text{Modified} \sim 1.6 \]

\[ \text{Lower energy} \]

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1. Paz-Soldan et al, Phys Plasmas 2014
2. Granetz et al, Phys Plasmas 2014
3. Aleynikov & Breizman, PRL 2015
Anomalous dissipation remains large at low energy
... what is going on ??

1 Paz-Soldan et al, Phys Plasmas 2014
2 Granetz et al, Phys Plasmas 2014
3 Aleynikov & Breizman, PRL 2015

Anomaly between predicted & observed critical electric field \((E_{crit})\) for RE growth shows strong energy dependence

- Previous results (without energy resolution) found\(^1\)\(^-\)\(^2\) HXR decay at anomalously high \(E/E_{crit}\)

- Energy–resolved measurements reveal \(E/E_{crit}\) threshold decreasing with increasing RE energy

- Extrapolated \(E/E_{crit}\) threshold for 6MeV RE in good agreement with theory incorporating pitch angle scattering & synchrotron effects\(^3\)

\[\text{Growth Rate (1/s)}\]

\[\text{Old } E/E_{crit} = 1\]

\[\text{Modified } \sim 1.6\]

\[\text{Lower energy}\]

C. Paz-Soldan et al, PoP 2018
Inclusion of kinetic instability improves agreement of bremsstrahlung observations with modeling

- Slope of distribution better matched when kinetic instability included
- Calculation w/ waves reproduces experimental $E/E_{\text{crit}}$ threshold
- Better match to synchrotron image

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Two regimes used to study RE:
Flat-top “quiescent” runaway (QRE) & post-disruption RE plateau
RE plateau formation: High energy RE instabilities correlated with suppression of RE plateau formation after Ar MGI
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- Small Ar quantities produce high energy RE & kinetic instabilities
- Increasing Ar reduces high-energy REs & suppresses kinetic instabilities

SEE A. LVOVSKIIY LATER THIS SESSION
RE plateau dissipation: Assimilation of impurities into RE plateau exhibits strong saturation

• At constant RE current, the # assimilated particles saturates as injected quantity increases…
RE plateau dissipation: Assimilation of impurities into RE plateau exhibits strong saturation

- At constant RE current, the # assimilated particles saturates as injected quantity increases...

- ... but the # of particles that can be assimilated increases with Ip
  - Further analysis needed to determine if linear

E. Hollmann et al 2018, in preparation
RE plateau dissipation: Assimilation of impurities into RE plateau exhibits strong saturation

- **DINA**: Fixed relationship between $I_p$ & $Z_p$ makes dissipation VERY difficult\textsuperscript{1,2}
  - $\uparrow$ Ar density $\rightarrow \uparrow$ VDE velocity $\rightarrow \uparrow E_{||}$
  - $E_{||}$ tends to “run away” from $E_0 \sim N_{ar}$

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1. Konovalov 2016 | IAEA
2. Kiramov & Breizman PoP 2017
RE plateau dissipation: Assimilation of impurities into RE plateau exhibits strong saturation

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- **DIII-D**: Faster RE plateau dissipation rate → Lower final loss current

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- **DIII-D**: Faster RE plateau dissipation rate $\rightarrow$ Lower final loss current

- Modeling effort underway to understand discrepancy

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2. Kiramov & Breizman PoP 2017
Recently excited kinetic instabilities in few eV RE RE RE plateau plasmas by reducing $n_e$ and changing $f(e)$

- **Instability Needs Collisionless Plasma**
  - Low Density or High $T_e$
- **QRE experiments met this condition**
  - Thermal $T_e$ is several keV
- **Post-disruption $n_e$ can be reduced**
  - Essential to see instabilities
  - Loop voltage modification important

QRE Experiments

![Stability Diagram](image)
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DIII-D developing new shell pellet technology to provide mitigation by core impurity deposition

**Concept:** Minimally perturbative shell transports radiating payload to core before ablating, releasing payload, & inducing TQ

**Potential Benefits:**

- **TQ:** “Inside-out” TQ mitigation → high radiated fraction
- **CQ:** Low-Z dust produces moderate CQ rate
- **RE:** Field stochastization & high \( n_e \) suppress RE seed

X-ray image of 3.6mm diameter 40μm thick B filled diamond shell

Izzo & Parks, PoP 2017

NW Eidietis/2018 TSDW/July 2018
Imaging indicates deep penetration of pellet before dust payload released

Pellet hits plasma edge...

30 mg B dust payload
Velocity ~ 230 m/s
Imaging indicates deep penetration of pellet before dust payload released

Pellet hits plasma edge...

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flies to core...
Imaging indicates deep penetration of pellet before dust payload released

30 mg B dust payload
Velocity ~ 230 m/s
Imaging indicates deep penetration of pellet before dust payload released

30 mg B dust payload
Velocity ~ 230 m/s

Location consistent with prediction of 1-D shell penetration model
Limited evidence of shell producing inverted temperature profile ("inside-out mitigation")

![Graph showing line integrated density](image)

**Line Integrated Density**

$10^{14}$ cm$^{-3}$ *m

**Time (ms)**

1660 1665 1670 1675 1680

**Z (cm)**

1660 1665 1670 1675 1680

**Te (keV)**

Before shell arrival

#176861 @ 1661.0 ms
Evidence of shell producing inverted temperature profile ("inside-out mitigation")

Before shell arrival

After shell arrival
DIII-D maintains a broad-based disruption mitigation program providing critical knowledge for the ITER DMS

- Qualifying SPI for use as the baseline ITER DMS technology
- Understanding the physics of RE formation and dissipation
- Exploring innovative paths for improving DMS technology

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