Effect of Locked-Modes on Impurity Spreading in MHD Simulations of Massive Gas Injection

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Theory and Simulations of Disruptions Workshop
Princeton, NJ
20 July 2016
• Disruption mitigation is applied as a last resort when a disruption is imminent and cannot be avoided by passive or active control.

• NTMs leading to locked-modes were found to be the most common root cause of disruptions in JET* (with other root causes also sometimes leading to mode-locking).

→ We can assume that disruption mitigation will very frequently be employed when large/locked islands are already present in the plasma.

• Disruption mitigation studies with pre-existing islands/locked-modes, using both massive gas injection (MGI) and shattered pellet injection, are part of a 2016 experimental Joint Research Target.

NIMROD extended MHD code is combined with KPRAD atomic physics code to model massive gas injection (MGI).

Beginning with DIII-D equilibrium, impurities are deposited as neutrals.

KPRAD calculates ionization, recombination and radiation cooling.

NIMROD calculates MHD response to edge cooling, diffuses and advects impurities along with main ion species.
Outline

Part 1: The physics of impurity plume expansion during massive gas injection (MGI)

Part 2: Results of MGI simulations with pre-existing islands
  - Comparison of 2/1 islands with different phases and amplitudes
  - The role of the n=2 mode
  - Simulation with pre-imposed 4/2 island

Part 3: Consequences for radiated energy fraction and toroidal peaking factor
PART 1: The physics of impurity plume expansion during massive gas injection (MGI)
Impurities spread along field lines fastest at the $q=2$ surface AND toward the high-field side.

Expansion is also toroidally asymmetric due to magnetic field gradient

Nozzle equation explains preferential HFS spreading:

Continuity

\[ \rho A U = \text{constant} \]

\[ BA = \text{constant} \Rightarrow \frac{d\rho}{\rho} + \frac{dU}{U} - \frac{dB}{B} = 0 \]

Momentum

\[ \rho UdU = -dp = -(dp / d\rho)d\rho = -C_s^2 d\rho \]

\[ \Rightarrow \frac{dU}{U} = \frac{1}{(1 - M^2)} \frac{dB}{B} \]

Flow starts at \( M < 1 \), is thwarted where \( dB/B < 0 \), accelerates where \( dB/B > 0 \)

Parallel spreading is driven by parallel heat transport.
Thermal equilibration happens faster at a low order rational surface.

$I@\nabla s$  

$T$  

$n$  

$p$  

$R_g$  

$D_w$
PART 2: Results of MGI simulations with pre-existing islands
Three simulations are initialized with 2/1 magnetic islands

- 0-phase, large island
- 180-phase, large island
- 0-phase, small island

MGI location is not aligned precisely with the x-point or the o-point for either phase.

Plotted @ 15°
TQ onset time, duration related to initial island width, phase respectively

- 0-phase, large island
- 180-phase, large island
- 0-phase, small island

\[ \text{Te (keV)} \]

\[
\begin{align*}
\text{R [m]} &
\end{align*}
\]

\[
\begin{align*}
\text{Time [ms]} &
\end{align*}
\]
Peak in radiated power is later for 180-phase with same size island.

At 0-phase, large initial flash in radiated power appears that is almost completely absent for 180-phase island.
Two radiation flashes in each case; difference in relative amplitude

- 0-phase, large island
- 180-phase, large island
- 0-phase, small island
After 1 ms, parallel spreading differs between the two phases.

180-phase, large island

0-phase, large island
With 0-phase, impurity plume breaks up into multiple branches, begins to spread more rapidly.
Change in impurity spreading coincident with appearance of 4/2 harmonic of 2/1
Changes in cooling near the 2/1 island are also evident when $n=2$ mode appears.

180-phase, large island

0-phase, large island

Contours of $-\Delta T$
Changes in cooling near the 2/1 island are also evident when n=2 mode appears.
Direct imposition of 4/2 island can force 180-phase to behave like 0-phase case

- Vlp xolvnrq# bk#lvbb# 725# rgh#gwhol# 524# rgh#cr#24# fps srgbw/# dp h# skdvh#bg# dp sdxgh# dw# 30skdvh#blujh# lvahl

- Dimh#4# jrzv#nr# fps sdledh# dp sdxgh# 5/# hyrov#rl#txdh# vlp lo# 0skdvh# fcdh

- Idw#shr#mg#blvnrq# idvk#h#n# edm#0 skdvh#edm#lk# vsrqvogl# 25# prghl

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PART 3: Consequences for radiated energy fraction and toroidal peaking factor
Conducted energy fraction defined by total energy lost minus radiated energy

- $Q_{\text{cond}} = \frac{\text{total energy lost}}{\text{radiated energy}}$

- $P_{\text{rad}}$

- $-\frac{d}{dt}[W_{\text{th}} + W_{\text{mag}}]$

- $-\frac{d}{dt}[W_{\text{th}}]$

- $Z_{uw} Z_{w} \overline{Z}_{uw} Z_{w}$
0-phase case has more uniform radiated power during most of the TQ.
0-phase case has more uniform radiated power during most of the TQ
Better mitigation when 4/2 mode is present
Conclusions

→ Magnetic topology plays a large role in determining impurity parallel transport
  • The presence of large islands affects the heat conduction and spreading of impurities at the rational surface
  • The break-up of the islands into smaller island chains enhances impurity spreading, and reduces average toroidal peaking and the conducted energy fraction

→ Evolution of magnetic topology is determined by combination of gas jet(s), pre-existing MHD, (and applied fields)
  • For a single gas jet, the appearance of the n=2 harmonic occurs only for some island phases.
  • A deliberately imposed 4/2 island produces a similar radiation pattern to the case with a spontaneously growing 4/2 mode

Future work: How do these results compare with DIII-D experiments? What about multiple jets? Higher-n harmonics?