3D Aspects of Massive Gas Injection for Disruption Mitigation

V.A. Izzo, N. Eidietis, D. Shiraki, et al.
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Goal of massive gas injection is to **isotropically** radiate plasma stored energy.

- **MGI valve**
- **# of valves & location(s)**
- **Radiation toroidal peaking factor (TPF)**
NIMROD modeling finds a more complicated relationship

- MGI valve
- # of valves & location(s)
- MHD
- Impurity transport
- Heat flux
- Radiation toroidal peaking factor (TPF)
Outline

PART I. Key 3D Physics of Massive Gas Injection

PART II. DIII-D TPF Predictions & Comparison with Measurements
PART I. Key 3D Physics of Massive Gas Injection

- **Pre-TQ**: None
- **Early TQ**: \( m/n > 1 \)
- **Late TQ**: \( m=1/n=1 \)
- **CQ**: Radial mixing

**MHD**
- None
- \( m/n > 1 \)
- \( m=1/n=1 \)

**Particle Transport**
- Plume expansion \( \parallel \) to B
- Radial mixing

**Heat Transport**
- Slow \( \perp \) conduction
- Fast \( \parallel \delta B_r \) conduction
- 1/1 convection
PART I. Key 3D Physics of Massive Gas Injection

NIMROD 4-stage MGI shutdown

MHD
- None
- $m/n > 1$
- $m=1/n=1$

Particle Transport
- Plume expansion $\parallel$ to $B$

Heat Transport
- Slow $\perp$ conduction
- Fast $\parallel \delta B_r$ conduction
- 1/1 convection

3D
Modeling finds impurities spread most rapidly toward the high-field-side (HFS)

- Magnetic nozzle effect accelerates impurities in direction of converging field lines; produces *asymmetric plume expansion* when injection is not at the midplane

→ cf. Izzo V.A., PoP 20, 056107 (2013) for HFS for LFS injection
In NIMROD model, two DIII-D jets spread in opposite directions toroidally.
In final phase of TQ, m=1/n=1 mode produces asymmetric heat flux, impurity mixing.

Central temperature drops rapidly as 1/1 mode grows large, saturates.

- As core begins to displace, core Te is still 3500 eV.
- 1/1 Phase is anti-aligned w/ gas jet: core moves up at 135°, away from MGI135L.

Te contours at 2.25 ms

Ne contours
In final phase of TQ, m=1/n=1 mode produces asymmetric heat flux, impurity mixing.

\[ T_e,_{\text{max}} /10 \text{ (eV)} \]

- Time (ms)

- \[ P_{\text{rad}} \text{ (MW)} \]

Te contours at 2.25 ms

1/1 displacement of core

\[ Z (m) \]

\[ dY/dt \]

- Time (ms)

Y=Mixing efficiency

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DIII-D n=1 phase is determined by jet location, rotation, external fields

• Mode first appears at phase determined by gas jet (anti-aligned) [as predicted by NIMROD]

• Generally, phases tend to rotate in direction of initial plasma rotation (pre-MGI), but order of magnitude slower (~1kHz)

• Final phase can be explained by combination of initial phase, plasma rotation, and torque from applied n=1 fields

Analysis by D. Shiraki
Experiments verify: the phase of the n=1 mode (relative to the gas plume) matters

**Pre-TQ phase:** Peaked toward gas jet, no effect of n=1 phase

**CQ phase:** Very symmetric, no effect of n=1 phase

**TQ phase:** Peaked (in some cases) away from gas jet, sinusoidal dependence on n=1 phase

![Graph showing the effect of applied n=1 phase on TPF](image-url)
The relative location of two gas jets matters (with respect to the field line pitch, n=1 mode phase)

DIII-D Normal Helicity (q=1)

DIII-D jets have same 1/1 mode phase, jets propagate away from each other toroidally

(C-Mod case: opposite 1/1 mode phase)

DIII-D Reversed Helicity (q=1)

In reversed helicity, jets have different 1/1 phase, propagate toward each other toroidally

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In reversed helicity simulation, DIII-D jets spread toward each other toroidally.
Summary of Part I: 3D MGI Physics

- Impurities spread preferentially toward HFS
  - NO EXPERIMENTAL CONFIRMATION

- 1/1 mode grows anti-aligned with MGI valve
  - OBSERVED ON DIII-D, BUT ROTATION AND ERROR FIELDS ALSO PLAY A ROLE

- Relative phase of n=1 mode to MGI valve affects TPF
  - CONFIRMED ON DIII-D AND JET

2+ valves MAY be better than one: depends on relative location of multiple valves w.r.t. each other and field line pitch
PART II. NIMROD Validation against DIII-D

→ DIII-D has two gas jets and two radiated power measurements

→ Both jets are closer to Prad90, both plumes propagate faster toward Prad210 (in normal helicity)
Definition of Toroidal Peaking Factor (TPF)

Given full toroidal information:

\[
TPF = \frac{\text{Max}(Prad)}{\text{Mean}(Prad)}
\]

Given limited diagnostics:

\[
\frac{\Delta P}{\Sigma P} = \frac{Prad_1 - Prad_2}{Prad_1 + Prad_2}
\]

\[
TPF = 1 + |\frac{\Delta P}{\Sigma P}| = \frac{\text{Max}(Prad_1, Prad_2)}{\text{Mean}(Prad_1, Prad_2)}
\]

Often integrate Prad over some phase of the disruption (say pre-TQ) and substitute Wrad for Prad in any of these equations.
DIII-D finds little or no variation in the TPF as a function of relative jet timing

\[ W_{\text{rad,}90} - W_{\text{rad,}210} \]
\[ W_{\text{rad,}90} + W_{\text{rad,}210} \]

\[ \text{TPF} = \frac{\max(W_{\text{rad}})}{\text{mean}(W_{\text{rad}})} \]
DIII-D finds little or no variation in the TPF as a function of relative jet timing.

\[ \Delta W_{\text{rad}} / \sum W_{\text{rad}} \]

TPF = \[ \frac{\max(W_{\text{rad}})}{\text{mean}(W_{\text{rad}})} \]

\[ W_{\text{rad},90} - W_{\text{rad,210}} \]

\[ W_{\text{rad},90} + W_{\text{rad,210}} \]
NIMROD predicts DIII-D measured values of $\Delta W_{rad} / \Sigma W_{rad}$
NIMROD predicts DIII-D measured values of \( \Delta \frac{W_{\text{rad}}}{\Sigma W_{\text{rad}}} \)

NIMROD results:

\( \times = \Delta \frac{W_{\text{rad}}}{\Sigma W_{\text{rad}}} \) (90 vs 210)
With just two measurements, $\Delta W_{\text{rad}}/\Sigma W_{\text{rad}}$ does not correspond to TPF

NIMROD results:

$\times = \Delta W_{\text{rad}}/\Sigma W_{\text{rad}}$ (90 vs 210)

$\bigcirc =$ High resolution TPF

Two jets do produce lower TPF than single jets...

...but DIII-D can’t measure TPF
NIMROD prediction: With both jets, TPF increases when \( I_p \) is reversed.

TPF increases for pre-TQ and TQ when current direction is reversed. Only increase during pre-TQ should be measurable.
Importance of the n=1 mode phase (as predicted by NIMROD) has been confirmed experimentally (DIII-D and JET)

In DIII-D experiments, gas jet location sets (initial) n=1 mode phase (anti-aligned, as predicted by NIMROD)

Levels of radiation asymmetries measured in DIII-D are reproduced by NIMROD, but comparison also shows DIII-D can’t measure TPF with any accuracy

NIMROD predicts preferential spreading of impurities toward HFS, experimentalists highly skeptical, reverse-Ip experiment will be informative; NSTX-U will also be a good test