Gas Jet Disruption Mitigation Studies on Alcator C-MOD

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Disruption mitigation with high-pressure noble gas jet

High-pressure noble gas jets can mitigate 3 problems arising from disruptions, without contaminating subsequent discharges.

1) **Divertor thermal loading**: sudden heat load ablates/melts divertor material  
**Solution**: Deliver large quantities of impurity into core plasma to dissipate high fraction of plasma energy by relatively benign, isotropic radiation

2) **Halo currents**: large mechanical $J \times B$ forces on vessel/first wall components  
**Solution**: Rapid thermal quench, resulting in a plasma that remains centered in vessel during current quench, substantially reducing vessel halo currents

3) **Runaway electrons**: Relativistic MeV electrons from avalanche amplification during current quench in large-scale tokamaks  
**Solution**: Suppression by large density of bound electrons in plasma volume.

**These issues are particularly severe for ITER**
Why do high-pressure noble gas jet experiments on C-Mod?

Gas jet mitigation has been studied in DIII-D (D. Whyte et al, PRL 89, 55001). It was postulated that the impurities penetrated as a neutral gas jet, since

$$P_{\text{jet}} \ (20-30 \, \text{kPa}) \geq P_{\text{plasma}} \ (8 \, \text{kPa vol. avg, 30 kPa on axis})$$

Alcator C-Mod has:

- $O(10\times)$ higher pressure
  - Good test of penetration hypothesis
- $O(10\times)$ higher $W_{\text{th}}$ density
- $O(10\times)$ higher $W_{\text{mag}}$ density
- Faster disruption timescale
  - Challenging test of ability to convert plasma energy to radiation on a fast enough timescale ($\sim1 \, \text{GW}$)
Specific goals of initial C-Mod experiments

• **Study penetration of gas jet/impurities:**
  — Fast camera, $T_e$ and X-ray profiles
  — NIMROD modeling, KPRAD modeling

• **Disruption mitigation:**
  — Halo currents (current quench time, vertical displacement)
  — Thermal deposition to divertor (IR camera, radiated fraction)

• **Engineering/operational issues:**
  — Optimization of gas jet system (quantity & speed at LCFS)
  — Reliability, reproducibility, post-disruption recovery

**Not addressed**: gas jet mitigation of actual disrupting plasma
  — Gas delivery speed; realtime disruption sensing
C-Mod gas jet system optimized based on DIII-D experience

Fast valve (ORNL)

Plenum (70 bar) filled with He, Ne, Ar, or Kr

Tokamak valve at port flange

Extraneous volume in high-pressure plenum, valves, and plumbing eliminated while still incorporating over-pressure relief safety.
C-Mod gas jet system optimized based on DIII-D experience

Outlet nozzle is extremely close to plasma edge (2-3 cm) to maximize gas injected into plasma.

Nozzle is pointed at plasma center

Injects $0.5\text{-}1.0\times10^{23}$ atoms in a few ms (plasma inventory is $1.5\text{-}3.0\times10^{20} \text{ D}^+, \text{ e}^-$)
Example gas jet shot (Helium)

Gas jet valve fires at t=0.8 s
Example gas jet shot (Helium)

Gas jet valve fires at $t=0.8$ s

Thermal quench occurs a few milliseconds later
Example gas jet shot (Helium)

Gas jet valve fires at $t=0.8$ s

Thermal quench occurs a few milliseconds later

Followed by current spike and current quench

- Loss of vertical stability
- Halo currents
Gas jet/impurity penetration
High-speed camera images indicate only shallow penetration of gas jet as neutrals.

Analysis of images of neutral gas jet shows predominantly toroidal flow, not deep radial penetration.
NIMROD simulations: MHD plays a major role

Fast cooling of edge region triggers MHD modes:

A 2/1 instability destroys outer flux surfaces, 1/1 mode flattens core temperature

Therefore only shallow \((r/a>0.85)\) impurity penetration is required to collapse core temperature on a fast timescale.
Actual C-Mod thermal quench for Ne, Ar, Kr closely resembles NIMROD calculations.

The thermal quench sequence is:

1) Initial cooling of outer edge by impurities

2) Cooling of outer region due to destruction of outer flux surfaces causing parallel thermal transport

3) Leveling of core temperature as 1/1 instability swaps magnetic axis with island formed in cold outer region—outer region reheats.

NIMROD case (20 µs time spacing) has lower S than experiment (400 µs time spacing)
Helium impurity penetration is somewhat different than Ne, Ar, Kr

Note: log scale
High-Z vs. Helium penetration characteristics.

Mitigation effectiveness does not seem linked to “strong” particle penetration found in He case.

Argon

~ Uniform $T_e$ drop

“Weak” particle penetration

But K-shell radiation:
$\text{Ar} @ \frac{r}{a} < 0.6$

Helium

Cold front propagates

Correlated He particle penetration

$\Delta t_{\text{Thermal Quench}}$
- 1.1 ms
- 0.6 ms
- 0.1 ms

$\Delta t_{\text{TQ}}$
-2
Mitigation of halo currents
Effect of gas jet on current quench

Typical (no gas jet)

Argon gas jet

Faster current quench

Less vertical displacement

Less halo current in divertor
Halo current reduction improves with Z
Mitigation of thermal deposition to divertor surfaces
Fraction of energy radiated increases with $Z$
IR imaging of divertor surfaces

Temperature image from IR camera
IR imaging of divertor surfaces

Thermal deposition is not toroidally uniform, but rather concentrated at leading edges
Gas jet reduces energy deposition on divertor surface
Gas jet reduces energy deposition on divertor surface

Temperature differences evident during cooldown
Summary: Operational results

• Helium, neon, argon, and krypton gas jets used successfully
• Very reproducible effects and timing (± 300 µs)
• Proved to be benign – no problem with following discharge
• No runaways generated (unlike with high-Z killer pellets)
Summary: Gas jet/impurity penetration

• Impurities do **not** penetrate far into plasma as neutral gas.

For higher Z gas jets (Ne, Ar, Kr) NIMROD modeling shows:

• Edge $T_e$ collapse triggers rapidly growing MHD modes (2/1 and 1/1) and large ergodic field regions, leading to rapid core $T_e$ collapse.

For He gas jet:

• Details of He ion influx are different than higher Z gases.

**Conclusion:** Since deep gas jet penetration is not required, gas jet mitigation is plausible in ITER and reactors.
Summary: Disruption mitigation

• Halo currents are reduced by as much at 50%
  — Faster current quench → less vertical displacement
  — Improves with Z of gas (higher resistivity)

• More plasma energy is converted to benign radiation
  — Less heating of divertor surfaces
  — Radiated energy fraction improves with Z of gas

**Conclusion**: Radiated power levels are high enough to affect energy balance on the disruption timescale. Higher Z impurities, which are better radiators, are more effective.
Future work

• Extend to higher performance plasmas
  — Higher $W_{th}$: 0.11 MJ → 0.25+ MJ (ITER energy densities)
  — Higher $I_p$: 1 MA → 2+ MA

• Gas jet mitigation of disrupting plasmas
  — Fire into programmed VDE’s
  — Gas flow rate through system may matter → possible tradeoff in $Z$ of gas (higher speed vs better radiator; mixed gases)
  — Realtime disruption sensing and gas jet firing (ultimate goal)

• Further analysis of energy accounting (particularly for He);
  Address toroidal symmetry questions; NIMROD modeling using KPRAD, NIMROD modeling of halo current reduction; etc.
Related talks and posters

Disruption Studies On C-MOD: Mitigation & Hydrogen/ Deuterium Fuel Recovery, D. Whyte et al, RO3.00005 (Thurs. pm)

Simulations of disruption mitigation by high-pressure gas jet on Alcator C-Mod, V. Izzo et al, KP1.00008, (Wed. am)

Massive Gas Injection System for Disruption Mitigation on the DIII-D Tokamak, T. Jernigan et al, CP1.00026 (Mon. pm)

Study of Transient Gas Flow Through Tubes Applicable to Disruption Mitigation in Tokamaks, M. Bakhtiari et al, BP1.00014 (Mon. am)