Disruption Studies on Alcator C-Mod: Gas-Jet Mitigation & Hydrogen /Deuterium Fuel Recovery

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Gas Jet Disruption Mitigation
Gas jet disruption mitigation on Alcator C-Mod: Reductions in halo forces and thermal loads without runaway electrons

\[ B = 5.4 \text{ T} \hspace{1cm} V = 1 \text{ m}^3 \]
\[ T_0 \sim 3 \text{ keV} \hspace{1cm} n \sim 3 \times 10^{20} \text{ m}^{-3} \]

Metal walls

ORNL gas jet /w 2 m tube:
\sim 10^{23} \text{ atoms in } \sim 5 \text{ ms}

**Natural VDE**
- \( I_p \) (MA)
- \( Z_{\text{centroid}} \) (m)
- \( I_{\text{halo}} \) (MA)

**Argon Gas Jet**
- \( I_p \) (MA)
- \( Z_{\text{centroid}} \) (m)
- \( I_{\text{halo}} \) (MA)
Frictional dissipation of gas “shock” important for gas delivery

Benchmarked gas dynamics code with friction

Gas flow into plasma coupled with KPRAD

The flow rate for CMOD gas tube (L=200 cm, D=0.94 cm)

Flow rate (10^-5 Torr/s)

Time (ms)

Volumetric deposition

Temperature (eV)

Current [MA]

Electron density [10^14 cm^-3]

Power, ohm [W cm^-2]

Power, rad [W cm^-2]
Coupled calculations of time-dependent gas delivery and energy/radiation balance agree well with C-Mod data

**Physics status**

- **In hand**: Gas delivery, Global energy balance, CQ equilibrium
- **Missing**: Neutral penetration in edge, core particle transport, MHD effects → NIMROD (V. Izzo)
Cold front propagation in core plasma is slower than gas sound speed on C-Mod: Helium case strongly breaks $1/M^{1/2}$ scaling

$$\Delta t = t_{\text{Thermal Quench}} - t_{\text{edge cooling starts}}$$

**DIII-D**

**C-Mod**

(Hollmann et al. IAEA 2004)
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: 
  Argon @ $r/a < 0.6$

### Helium

- Cold front propagates

- Correlated He particle penetration
Hydrogen / Deuterium Fuel Recovery Using Disruptions
Exploit rapid dissipation of plasma energy to wall surface in order to desorb H/D/T without damaging material surfaces.

- H/D/T forced into vacuum vessel and H\(_2\) and recovered by normal pumping.

- Expect threshold in local energy density for removal efficiency from Arrhenius dependence on H diffusion in Mo/B.

- **C-Mod goal:** Control H/D ratio after vent
  - Surface analysis shows H/D ~ 5-10 in near surface, due to H\(_2\)O adsorption.
  - Large starting H+D inventory:
    - H/(B+Mo) ~ 10-40% in first micron(s)
    - H inventory > 1000 Torr-L H\(_2\)
  - ~50% D\(_2\) wall pumping in quiescent shots?

- **ITER goal:** Routine in-situ tritium recovery
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**Energy density difference:**
Unmitigated disruption in C-Mod compared to radiative terminations in ITER.

**Disruptions with closed pump valves for H/D particle balance**

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**Graph:**
- **X-axis:** Stored energy at disruption (kJ)
- **Y-axis:** Gas recovered - Gas input (Torr-L)
- **Plots:**
  - **Plasma shots**
  - **No plasma**
Principles of $\text{H}_2$ desorption by disruption surface heating are generally validated.

Threshold for $\text{H}_2$ recovery with plasma $W_{th}$ and $T_{e,0}$

Recovered gas mix reflects plasma H/D composition:
*Disruptions are removing $\text{H}/\text{D}$ from near surface*
Effectiveness of disruption H/D recovery

Recovered ~30% H₂ in single operation day.
H/D ↓ ~35%
Wall fuel depleted

5-10x more efficient for H₂ recovery than typical techniques
Summary

- Gas jet disruption mitigation successful on high-field, high-pressure, all-metal Alcator C-Mod
  - Demonstrable reduction in halo forces, thermal loads & no runaways.
  - Benign: eliminated post-disruption “fizzles” on subsequent shots.
  - New model of gas flow & 0-D radiation compares well to data (e.g. termination timing, current quench time) except for MHD mixing.

- C-Mod data providing insights on coupled roles of gas delivery, impurity transport and MHD for mitigation.
  - “Strong” core particle penetration may not be necessary for mitigation.
  - Mixing gases may provide optimal gas delivery + impurity radiation.

- Promising initial results using controlled disruptions / terminations to recover H/D/T fuel from wall.