Real-time VDE mitigation with gas jet injection, and mixed gas jets on Alcator C-MOD

R. Granetz$^1$, S. Wolfe$^1$, D. Whyte$^1$, V. Izzo$^1$, M. Reinke$^1$, J. Terry$^1$, A. Bader$^1$, M. Bakhtiari$^2$, T. Jernigan$^3$, G. Wurden$^4$

1 MIT Plasma Science and Fusion Center
2 University of Wisconsin
3 Oak Ridge National Laboratory
4 Los Alamos National Laboratory

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Abstract

Experiments have been carried out in Alcator C-Mod to test the effectiveness of gas jet disruption mitigation of VDEs (vertical displacement events) with real-time detection and triggering by the C-Mod digital plasma control system (DPCS). The DPCS continuously computes the error in the plasma vertical position from the magnetics diagnostics. When this error exceeds an adjustable preset value, the DPCS triggers the gas jet valve (with a negligible latency time). The high-pressure gas (argon) only takes a few milliseconds to enter the vacuum chamber and begin affecting the plasma, but this is comparable to the VDE timescale on C-Mod. Nevertheless, gas jet injection reduced the halo current, increased the radiated power fraction, and reduced the heating of the divertor compared to unmitigated disruptions, but not quite as well as in earlier mitigation experiments with vertically stable plasmas. Presumably a faster overall response time would be beneficial, and several ways to achieve this will also be discussed.
Gas jet disruption mitigation: Pre-programmed vs real-time

All previously reported experiments with gas jet disruption mitigation on C-Mod have been done on stable, non-disrupting plasmas.

• Plasma was not moving prior to gas jet injection
• Valve trigger was fired at pre-programmed time
• Therefore the time response of the gas delivery system (~ 4 ms) was not an issue.

Various mitigation-relevant parameters were measured and compared to ‘naturally occurring’ disruptions.
Pre-programmed gas jet injection is successful at disruption mitigation

With argon gas jet:

- Halo current reduced by 50%
- Divertor tile heating reduced by 80°C

Radiated energy fraction increases with $Z_{\text{gas}}$, reaching ~80-90%

Halo currents reduced ~50%

Divertor tile heating reduced ~60%
Ultimate goal: **real-time** disruption mitigation with gas jet injection.

For our first attempt at this, we have used VDEs, since we have simple and reliable methods for reproducibly making a VDE and for early detection of a VDE.

- Response time of gas delivery system now becomes an issue, since it is similar to VDE disruption timescale (a few milliseconds)

- Mitigation of VDEs may be more difficult than mitigation of non-VDE disruptions (high $\beta$, locked mode, density limit, etc.)
Mitigation of VDEs on Alcator C-Mod

3 different experiments were done to test argon gas jet mitigation of VDEs:

1) Pre-programmed turnoff of vertical position control, and pre-programmed firing of gas valve
   - Compare mitigation of static vs moving plasma
   - Determine trigger level (vertical displacement at which gas jet is fired)

2) Pre-programmed turnoff of vertical position control, and real-time detection of VDE by DPCS and firing of gas jet

3) Cause VDE by ramping up elongation, and real-time detection of VDE by DPCS and firing of gas jet
Example of VDE initiated by turning off vertical position feedback control

- Trigger level of 11 mm works well (a=22 cm)
- Rapid termination $I_{\text{halo}}$ mitigated
Example of VDE initiated by ramping up elongation (leaving vertical feedback on)

Elongation ramped up: 1.68→1.78

Plasma becomes vertically unstable and gas jet is trigger by DPCS
Halo current mitigated, but not quite as well as with vertically stable plasmas

For comparison, in vertically stable plasmas halo current is reduced by 50% with pure argon gas jet
Radiated energy fraction increased, but not quite as much as with vertically stable plasmas.

For comparison, in vertically stable plasmas, $E_{\text{rad}}/W_{\text{tot}}$ is $\geq 80\%$ with pure argon gas jet.
Summary of real-time mitigation of VDEs

Real-time VDE prediction and gas jet firing works, and mitigation is good, although not quite as good as with pre-programmed, midplane disruptions.

– Response time of gas delivery system may be an issue
– Response time is dominated by flow speed of argon in the gas tube
Mixed gas jets can speed up response time

Flow speed (~ sound speed) of lighter, low-Z gas is faster than heavier, high-Z gas, but high-Z is much better at disruption mitigation.

Small amounts of a heavy gas mixed in with a lighter gas will flow at approximately the sound speed of the lighter gas, since the flow is in the viscous regime. This is a simple way to speed up the delivery of high-Z gas to the vacuum chamber. (M. Bakhtiari, et al, DPP06/J01.00006)

— Helium carrier gas used on C-Mod
— 5%-35% argon mixed in
C-Mod gas jet system was not designed with gas mixing in mind

We started the run day by filling the gas jet plenum with pure helium.

After each gas jet shot, we topped off the plenum from a bottle of 50/50 He/Ar mix. This gradually increased the argon fraction throughout the run day.
Argon fraction is measured in-situ with residual gas analyzer after the discharge.
10-15% argon fraction optimizes $T_e$ collapse

- 100% helium (red) does not collapse $T_e$ effectively
- $\geq 20\%$ argon does not collapse $T_e$ as quickly
10% Argon mixture optimizes mitigation response time & radiation efficiency

Experiments

Radiated Energy (MJ)

Total initial energy ~0.7 MJ

$t_{\text{CQ}} - t_{\text{Inj}}$ (ms)

Argon Fraction (%)
Mixtures provide fastest overall response time

~ 2 ms

M. Bakhtiari, *et al.*, DPP06/J01.00006
Summary

• Real-time gas jet mitigation of VDEs was successful
  — Mitigation was not quite as good as for stable, midplane plasmas
  — Time response of gas jet delivery may be an issue

• Mixing argon into helium carrier speeds up response time by ~ 2 ms while still resulting in good mitigation

Near-term plans: real-time detection and mitigation of locked mode disruptions