1 Purpose of experiments

Include immediate goal of the experiments, scientific importance and/or programmatic relevance. Refer to any relevant program milestones or ITER R&D commitments. This is the “sales pitch” for your use of a C-Mod run day.

The goal of this experiment is twofold: (1) to commission the second disruption mitigation gas jet; and (2) to begin to study the performance of the Alcator C-Mod disruption mitigation system with the second gas jet installed, especially as regards the toroidal radiation asymmetries observed in earlier gas jet experiments. This miniproposal continues an ongoing line of research \[1, 2, 3, 4, 5, 6\] into massive gas jet disruption mitigation (MGI-DM), aimed at understanding the physics of what occurs during a mitigated disruption, and informing the design of disruption mitigation systems for ITER and for future reactors.

2 Background

Discuss physics basis of the proposed research, prior results at Alcator or elsewhere, and any related work being carried out separately (in other Alcator C-Mod miniproposals).

2.1 Tokamak disruptions

Major disruptions (today usually just called “disruptions”) are events in tokamak plasma discharges in which the stored thermal energy of the plasma is suddenly lost (over \(\approx\) ms timescales, \(<\tau_E\)) and not recovered by re-heating; the toroidal plasma current then resistively ramps down on approximately an \(L/R\) timescale. The loss of stored energy (plasma pressure) is known as the “thermal quench” (TQ), and the subsequent ramping-down of plasma current is known as the “current quench” (CQ). In tokamaks today, disruptions are a common event, with a significant fraction of plasma discharges ending this way \[1\]. (This fraction is known as “disruptivity.”)

Due to its general definition (roughly: any event that suddenly ends the plasma discharge with a loss of stored thermal energy and subsequent termination of the plasma current), there are many classes of disruptions, such as density-limit disruptions (thought to be a radiative instability), stability limit disruptions (in which a parameter like \(\beta\) or \(q\) crosses a stability limit), or vertical displacement events (VDEs, in which control of the vertical position of the plasma column is lost). In all cases, the stored thermal (pressure) and magnetic (current) energy in the plasma can be deposited onto localized plasma-facing surfaces. In shaped plasmas, this deposition is often localized to the divertor region due to the heat conducting down field lines in the scrape-off layer to the divertor, or due to vertical position control being lost (either after the TQ, or in the case of a VDE, before/simultaneous with the TQ).
This localized deposition of energy—nearly 1 MJ in C-Mod, and scaling as $R^3$ to larger machines—has the potential to cause PFC damage in ITER and in reactors, requiring unscheduled maintenance to remove the leading edges that are created due to melting of high-Z metallic PFCs. In addition, currents flowing in the cold, force-free plasma ($\vec{J} \times \vec{B} \approx 0$) short out through the vacuum vessel, causing “halo currents” to flow, which interact with the toroidal magnetic field and produce large loads on the vacuum vessel and divertor components.

2.2 Disruption mitigation

Because of the potential damage to plasma-facing surfaces from unmitigated disruptions, research has proceeded into how to mitigate their effects. Several techniques have been developed, such as “killer pellet” injection, shattered pellet injection, liquid jet injection, or the technique used on Alcator C-Mod, massive gas jet disruption mitigation (MGI-DM).

On Alcator C-Mod, the MGI-DM system consists of a high-pressure gas plenum connected by a fast valve and a simple length of stainless steel pipe to the edge of the plasma. When the system is triggered\(^1\), a large amount of gas (> $10^{23}$ electrons, typically a mixture of 85% Ar + 15% He) is injected suddenly into the plasma, which triggers a disruption.

The difference is that this induced disruption repeatably radiates the stored energy of the plasma over the entire first wall. The addition of such a large amount of highly radiative species (argon) along with the helium to increase the sound speed of the delivered gas [6], quickly reduces the plasma temperature to 5–10 eV, increasing the resistivity of the post-TQ plasma and thus decreasing the duration of the CQ. Time traces of some key parameters during a gas jet mitigated disruption (C-Mod shot 1090925014, part of MP 567) are shown at right in figure 1.

The C-Mod disruption mitigation system has been upgraded in the Summer 2011 opening, and now consists of two independent gas jets.

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\(^1\)On Alcator C-Mod, the disruption mitigation system is currently pre-programmed. In “disruption prediction” experiments, and in future reactors, the mitigation system will be triggered by the plasma CODAC and/or machine protection systems. These experiments are not currently performed on C-Mod.
each able to be charged with their own gas mixture and triggered at independent times. The goal of this experiment is to commission the new gas jet equipment, but also to compare the behavior of mitigated disruptions using both gas jets to that of mitigated disruptions triggered by the original, single gas jet.

2.3 Radiation asymmetry in mitigated disruptions

It has been found in experiments on Alcator C-Mod and elsewhere that the energy is not radiated evenly over the entire plasma-facing surface during gas jet mitigated disruptions: it has significant toroidal and poloidal asymmetries [4]. Mitigated disruptions on C-Mod are investigated using the diagnostics shown in figure 2.

The yellow-shaded chords in the AXA and AXJ arrays in figure 2 have been used in past experiments [7] to diagnose the radiation asymmetry. When the total time-integrated radiation seen through the entire disruption (TQ and CQ) is compared between AXA and AXJ, ratios varying from 1.1–2.4 are seen, with AXA always receiving more radiation (likely because the AXA chords “see” the gas jet, while the AXJ chords look the other way). Figure 3 shows time traces of the radiation power seen on the two diode arrays for a very symmetric, and a highly asymmetric disruption mitigation experiment.

It should be noted that the AXUV diodes used to diagnose radiation asymmetry in these experiments have reduced sensitivity between approximately 400 and 50 nm wavelength (violet visible light to vacuum UV). Thus, the radiation asymmetry seen by the AXUV diodes does not serve as proof of the absolute total radiation asymmetry. However, the total time-integrated radiation energy seen by a $2\pi$ bolometer of the gold-on-kapton foil type [8] is assumed to correlate with the time-integrated radiation seen by a $2\pi$ AXUV diode (known as the “$2\pi$ bolometer diode”) and thus that the radiation during mitigated disruptions seen by the AXUV diodes is a good proxy for the total radiation across the entire spectrum.

The issue of radiation asymmetry in mitigated disruptions is extremely important for ITER, since it is estimated that a peak-to-average ratio of the radiated power during the TQ of 2 or greater could lead to localized beryllium first wall melting [9].

One of the main goals of the second gas jet system installed on Alcator C-Mod (see section 2.4) is to determine if using multiple gas jets (or by phasing the multiple gas jets, using different gases in each one, etc.) can reduce the radiation asymmetry. This is in addition to the other interesting science that can come out of the use of multiple gas jets, such as its effect on halo currents, TQ and CQ duration, radiated energy fraction (that is, the fraction of plasma stored energy that is radiated during the mitigated disruption), etc.
2.4 The second gas jet system

The second gas jet system, essentially an identical copy of the first one, albeit at a slightly different poloidal location due to equipment constraints (see figure 5) has been installed at F-port during the Summer 2011 opening. Photographs of the original gas jet (at B-port) and the new one (at F-port) are shown in figure 4.

See miniproposal 424 [10] for additional information about the rationale for the gas jet disruption mitigation system. In general, this experiment aims to begin to test all of the elements of an effective gas jet disruption mitigation system with both one and two gas jets:

- Reduction of halo currents vs. unmitigated disruptions
- Radiated energy fraction
- Current quench duration
- Radiated energy asymmetry
- Pre-thermal quench duration
- Presence of MHD modes during pre-TQ phase (and the link to the radiated energy asymmetry [5])

3 Approach

What your experiment will actually do, and why you will do it that way. Describe the methodology to be employed and explain the rationale for the choice of parameters. Describe the analysis techniques to be employed in interpreting the data, if applicable. If the approach is standard or otherwise self-evident, this section may be absorbed into the Experimental Plan.

For these initial experiments with one and two gas jets, we will run a typical, non-disruptive 800 kA, 5.4T fiducial target plasma, with RF heating in the second phase (not required in the first phase). We will pre-emptively fire in gas jets using the now-standard 85% He + 15% Ar disruption mitigation gas. It is anticipated that several shots will be required to set the timing of the gas jets relative to each other.
In addition, the new disruption mitigation bolometry (DMBolo) system will likely need adjustments (to transimpedance gain) after each of the first few shots.

We will then study how the thermal and current quench times, vertical and horizontal plasma motion, halo currents, and radiated energy efficiency ($W_{\text{rad}}/W_{\text{th}}$) are affected by the use of one or two gas jets, and the relative timing between the two gas jets. Most importantly, the DMBolo system will collect information about the toroidal asymmetry in the radiated energy during the mitigated disruption.

I-mode target plasmas are specified for the second (RF-heated) phase of this experiment because of their greater reproducibility of target conditions at the time of the gas jet firing compared to H-modes.

4 Resources

4.1 Machine and plasma parameters

Give values or range for all of the following:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toroidal field</td>
<td>5.4 T</td>
</tr>
<tr>
<td>Plasma current</td>
<td>800 kA</td>
</tr>
<tr>
<td>Working gas species</td>
<td>Deuterium (D$_2$)</td>
</tr>
<tr>
<td>Density</td>
<td>$\bar{n}_e \approx 1.5 - 2.0 \times 10^{20} \text{ m}^{-3}$</td>
</tr>
<tr>
<td></td>
<td>$n_{04} \approx 0.8 - 1.2 \times 10^{20} \text{ m}^{-2}$</td>
</tr>
<tr>
<td>Equilibrium configuration</td>
<td>Reference shot 1110113020 (LSN for L-mode)</td>
</tr>
<tr>
<td></td>
<td>1110323027 (USN for I-mode if RF available)</td>
</tr>
<tr>
<td>Pulse length, typical current and density waveforms, etc.</td>
<td>As in shot 1110113020 or 1110323027.</td>
</tr>
</tbody>
</table>

Boronization required?

If yes, specify whether overnight or between-shot, how recently needed, and any special conditions.

If RF is available, run any time after the first boronization of the campaign. If no RF available, boronization is not required.

4.2 Auxiliary systems

List requirements for the following Alcator C-Mod auxiliary systems:

<table>
<thead>
<tr>
<th>System</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICRF (power, pulse length, phasing)</td>
<td>Not required for initial L-mode experiments; for I-mode targets, request 1.0–3.0 MW, turning on at $t = 0.6$ s, until (induced) disruption at $t = 1.0$ s</td>
</tr>
<tr>
<td>LHCD (power, pulse length, phasing)</td>
<td>Not required</td>
</tr>
<tr>
<td>Pellet injection (list species)</td>
<td>N/A</td>
</tr>
<tr>
<td>Impurity injection (laser blow-off)</td>
<td>Not required.</td>
</tr>
<tr>
<td>Diagnostic neutral beam</td>
<td>Not required.</td>
</tr>
<tr>
<td>Special gas puffing</td>
<td>Disruption mitigation gas jets at B-port and F-port with 85% He / 15% Ar gas mixture</td>
</tr>
<tr>
<td>Cryopump</td>
<td>Not required</td>
</tr>
<tr>
<td>Non-axisymmetric coils (list connections and current)</td>
<td>Not required.</td>
</tr>
<tr>
<td>Other</td>
<td>None</td>
</tr>
</tbody>
</table>
4.3 Diagnostics

List required diagnostics, and any special setup or configuration required, e.g. non-standard digitization rate.

Only a base set of diagnostics (magnetics, TCI) will be required, however, Thomson, fast ECE (FRCECE), fast CXRS, and IR imaging are desired if possible. The full set of bolometric diagnostics (foil bolometers and AXUV diodes, both $2\pi$ and radial), plus the DMBolo system (disruption mitigation AXUV diodes), and the fast magnetics pickup coils should be operational.

Sensitive diagnostics should have their gate valves or shutters closed prior to this run to avoid damage due to the large pressure pulse created by the gas jet injectors.

4.4 Neutron budget

Estimate the neutron dose rate at the site boundary. Give basis for estimate (e.g. refer to previous shots).

Based on the target shot planned to be used for the initial phase of this run (1110113020, with no RF heating), it is anticipated that the neutron production rate will be below $1.0 \times 10^{11}$ s$^{-1}$, and thus total neutron production for the day will be very low.

If RF is available and the I-mode target shot (1110323027) is used, the neutron production should be approximately $0.6-1.0 \times 10^{13}$ s$^{-1}$ during ICRF operation (from 0.6–1.0 s during each shot). Thus, total neutron production for the day (20 useful shots) should stay below the occupational warning limit of $10^{14}$ neutrons.

5 Experimental plan

5.1 Run sequence plan

Specify total number of runs required, and any special requirements, such as consecutive days, Monday runs, extended run period (10 hours maximum), etc.

We anticipate that this experiment will require two ordinary-length run days: one for L-mode target plasmas and one for RF-heated I-mode targets. The first of these run days can be during the preliminary phase of the campaign, when not all diagnostic and heating systems are fully functioning.

The use of the gas jet disruption mitigation system has in the past led to the loss of one or more subsequent shots, reducing the number of useful discharges in a run day, although this was not the case in one recent experiment (run 1090925).

5.2 Shot sequence plan

For each run day, give detailed specification for proposed shot sequence: number of shots at each condition, specific parameters and auxiliary systems requirements, etc. Include contingency plans, if appropriate.

The first run day will consist of a planned 20–24 useful shots. In all cases, the gas jet system will be triggered at $t = 1.0$ s ($\pm$ a few milliseconds for staggered triggering of each gas jet).

1. Commissioning of gas jets. Load LSN target (1110113020) and make field/current adjustments as necessary. Fire gas jet (with standard 85% Ar, 15% He disruption mitigation gas mixture) into identical 800 kA, 5.4 T, $n_0 t_0 \approx 0.8 \times 10^{20}$ m$^{-2}$ plasmas (see section 4.1). Repeat twice with each of two gas jets (B- and F-port). Fire gas jet at B-port, then (new) gas jet at G-port, then B-port, then G-port. (4 shots total)
2. **Simultaneous operation of two gas jets.** Fire both gas jets at the same time into identical plasma. Repeat three times to figure out any unexpected offsets in the timing of each jet. Attempt to get the two gas jets to fire at the exact same time. Up to four shots allocated for this. (If it is attained earlier, move on to step 3.) (3–4 shots total)

3. **Staggered gas jet operation scan.** This is a scan of the advancement time between triggering to each gas jet. Defining $\Delta t \equiv t_{\text{trig,G}} - t_{\text{trig,B}}$ (i.e., the length of time between the triggering signal being sent to the B-port and the G-port gas jets, such that a positive $\Delta t$ means that the G-port gas jet is fired after the B-port jet), repeat into identical $(800 \text{ kA}, 5.4 \text{ T}, n_0 \approx 0.8 \times 10^{20} \text{ m}^{-2})$ plasma with $\Delta t = -2.0, -1.0, 1.0, \text{ and } 2.0 \text{ ms.}$ ($\Delta t = 0$ was already covered in the last step.) (4–6 shots total).

4. **q-scan.** Repeat with B-port gas jet alone; G-port gas jet alone; both gas jets at the same time ($\Delta t = 0$); and both gas jets with $\Delta t = \pm 1.0$ ms at $5.4 \text{ T}$ with currents of $600 \text{ kA}, 1.0 \text{ MA, and } 1.2 \text{ MA.}$ Adjust density to maintain fixed $T_e$. This step will be completed on the first day only if time permits. (9 shots total).

On the second day, we first complete step 4 from the first run day (if not completed then), and perform a scan of $W_{th}$ in I-mode (target 1110323027) using 1.0–3.0 MW of ICRF power from D and E antennas (additional power from J antenna if available). Finally, if possible, the current is varied in order to perform a q-scan in I-mode.

1. **Complete L-mode q-scan from day 1.** See step 4 from first run day.

2. **Two gas jets into RF-heated I-mode plasmas.** Load target I-mode shot (1110323027) at $800 \text{ kA}, 5.4 \text{ T, upper single null topology.}$ Repeat staggered gas jet and single gas jet operation into I-mode target according to lessons learned from first day. (4–6 shots total).

3. **$W_{th}$ scan in I-mode.** Increase heating from 1.5 to 3.0 MA (or even further, depending on availability of J-antenna) and fire gas jet at $t = 1.0 \text{ s.}$ (2–3 shots).

4. **q-scan in I-mode plasmas** Increase current to 1.0 and 1.2 MA and fire gas jet at $t = 1.0 \text{ s.}$ (2–3 shots).

6 **Anticipated results**

*Discuss possible experimental outcomes and implications. Indicate if the experiment may be expected to lead to publications, milestone completions, improved operating techniques, etc. Indicate if the experiments are intended to contribute to a joint research effort, or an external database.*

It is anticipated that interesting results will be obtained by the use of two gas jets, regardless of their success in reducing the radiation asymmetry. If the use of the two gas jets (in general, or due to specific timing between the jets) is successful at reducing the radiation asymmetry, this would be a very important result for ITER. If it is unsuccessful, it would still be interesting from a physics perspective, and might shed light on the link between MHD modes and the radiation asymmetry that was identified in 2010 [5].

This research will be presented as a poster or talk at conferences (APS-DPP 2012 and possibly HTPD 2012). In addition, understanding the cause of the observed radiation asymmetry in gas jet mitigated disruptions has been identified as a high-priority issue for ITER (see, e.g., [11]). The results of this work will directly inform the choice of the number of gas jets in the ITER design. It is anticipated that the experimental observations of disruption mitigation with two gas jets will lead to a peer-reviewed publication. If the observations lead to a theory of what is occurring during a mitigated disruption, and/or what is causing the radiation asymmetry, a second publication could result. This experiment will also contribute to G.M. Olynyk’s thesis work.
References


