Disruption mitigation experiments with one and two gas jets on Alcator C-Mod

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We do not yet have a complete theory of the physics governing the thermal quench in a gas jet rapid shutdown, but hints emerge.

1. Massive gas injection is one of the leading candidates for rapid shutdown of ITER plasmas. Toroidal radiation peaking, however, could cause localized wall melting even in the case of a successful gas injection.

2. Experiments on Alcator C-Mod have shown that rapid shutdown by massive noble gas injection is feasible with multiple, toroidally separated gas jets.

3. Firing multiple gas jets with optimum timing (gas hits plasma at same time) can actually increase the toroidal radiation peaking factor.

4. There is a “sweet spot” with slightly off-synchronous timing.

5. The traditional view of a massive gas jet rapid shutdown as preTQ–TQ–CQ may be too simple. The current flattening sometimes does not begin until ~200 μs after the initial TQ flash is complete. During this time, the plasma continues to radiate (a mixture of stored thermal and magnetic energy?) MHD modeling is needed to illuminate what is going on in this phase.

6. Reliable rapid shutdown in ITER without severe radiation peaking in the thermal quench will require multiple gas jets, possibly firing asynchronously.
A massive gas injection rapid shutdown can be thought of as a controlled, benign disruption that preempts a harmful disruption.

- **In a massive gas injection rapid shutdown**, a large quantity of radiative species (typically a noble gas such as He, Ne, Ar) is injected so that plasma stored energy is radiated evenly over the entire first wall, rather than being conducted along open field lines to solid surfaces.
  - Use optimized 15% Ar / 85% He on C-Mod (Bakhtiar et al. 2011) Nucl. Fus. 51, 063007
  - Benefits include reduced halo currents, high radiated energy fraction, more reliable restart (next shot less likely to be a fizzle/NSD).
  - Risk to ITER beryllium first wall even in the case of a successful rapid shutdown if toroidal radiation peaking factor is \( \gtrsim 2 \).
- Traditionally two phases to disruption – **thermal quench** (stored thermal energy), and **current quench** (stored magnetic energy).
  - Thermal quench is largest concern for ITER
Alcator C-Mod has a massive gas injection system, recently upgraded to use two toroidally separated injectors.

- Fast valves supplied by Oak Ridge (ORNL)
- Solenoid valves open using eddy currents
- Stay open for ~10 ms and then close again by spring; seal by gas pressure against seat
- About 1300–1400 torr-ℓ gas injected
A toroidal array of wall-mounted single-chord wide-viewing AXUV diodes with gain optimized for disruptions has been fielded.

- Viewing through 100 µm pinhole in 15 µm (0.0006”) Mo foil
- Locations on wall constrained by available space on vessel midplane

The two gas injectors fire into the low-field side of the plasma at similar poloidal positions.

Each wall-mounted diode sees a narrowly collimated poloidal “slice” of the plasma in the toroidal direction.
The thermal quench event seems to have two discrete phases on radiated power diagnostic – a fast pulse, and then a slower one.

**pre-TQ:** Gas penetrates plasma, cooling front moving in

**TQ:** Cooling front reaches $q=2$ surface, large MHD causes rapid transport of energy from core to radiative “mantle” – thermal energy being released

**CF:** Current redistribution (flattening) – mixture of thermal energy and magnetic energy

**CQ:** Current decays away – magnetic energy being released

- How the duration of each phase scales with machine size will be important for determining the effect on the wall of ITER.

TS data indicate core plasma is < 500 eV by now
Toroidal array of diodes observes time-dependent toroidal radiation asymmetry in massive gas injection rapid shutdowns.

- Asymmetry can be large during TQ and CF phases.
- Often observe a rotating peak, which usually locks before onset of CQ.
- Peaking factor tends to be modest in CQ, and goes to unity later in CQ.
The presence of low-\(n\) MHD modes can be diagnosed using fast magnetic pickup coils on stalks and in the limiter.

- Fit using least-squares rather than typical fluctuation methods because in C-Mod disruptions, growth rate \(\sim\) rotation rate
- \(n = 1\) component dominates over \(n = 2\)
- Mode grows \(\sim\)linearly, saturates, and then thermal quench begins.
- Coils saturate at onset of TQ – can’t get reliable fit to phase or magnitude after this
Most gas jet rapid shutdowns have a linear growth phase to the \( n=1 \) MHD mode, prior to the main TQ event

- Linear growth phase lines up approximately with cooling front reaching radius of \( q = 2 \) surface, as indicated by fast ECE radiometry (2\textsuperscript{nd} harmonic X-mode)

- Consistent with existing theory of thermal quench onset – triggered by (2,1) and then (1,1) internal kink modes triggered by cooling front reaching \( q = 2 \) surface


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The toroidal radiation asymmetry can be estimated for the various phases of the rapid shutdown using AXUV diode data.

- Thus the TPF as calculated from toroidal diodes is a floor on the true TPF.
In 3.6 MW ICRF-heated I-mode plasmas, the toroidal radiation peaking factor is lowest when the gas jets are not synchronous.

- Identical targets (3.6 MW auxiliary heating, $B_{\text{tor}} = 5.6$ T, $I_p = 1.1$ MA, $<n_e> \sim 1.1-1.2 \times 10^{20}$ m$^{-3}$, $q_{95} = 3.3$) I-mode plasmas

- Scan “stagger time” of gas jets
  - $\Delta t = 0$ means gas hits plasma at same time
  - $\Delta t < 0$ means F-jet hits first; $\Delta t > 0$ means B-jet hits first

- Define toroidal peaking factor (TPF) as the peak value divided by the average of five diodes.

- Peaking factor in TQ flash ($\triangle$) has TPF $> 1.5$ for single jet or for synchronous jets; lower for two jets with offset of $\sim 0.5-1.0$ ms.

- For single jets, TPF gets lower when you include CF phase; implication is that CF/CQ are more symmetric.
  - Not the case for synchronous
In 3.6 MW ICRF-heated I-mode plasmas, the toroidal radiation peaking factor is lowest when the gas jets are not synchronous.

- Black circles are the “synchronous” gas jet rapid shutdowns.
- Diode signals integrated through initial TQ flash only.
- Peaking generally on opposite side of machine from gas injection for single-jet.
- For two jets, strong peaking on one side.
Similar behavior is seen in 1 MW ICRF-heated L-modes. The optimum toroidal peaking factor is seen with asynchronous jets.

- Comprehensive scan of gas jet stagger time, including single-jet shots
- Optimum results seen for approx. 1 ms offset in stagger time
- More consistent, lower TPF seen for firing F-jet first
  - Different poloidal position (lower, closer to X-point) – perhaps affecting TPF
A scan of elongation for inner-wall limited plasmas reveals different behavior at low and high elongation.

- Scan plasma elongation at approx. constant safety factor (3.5–3.7) and current (750 kA), by varying field

- At low elongation, there seems to be a “clean” TQ, followed by the magnetic stored energy being radiated once the indicated current starts increasing.

- At higher elongation, more radiated power during intermediate “CF” phase before current starts increasing.
For inner-wall limited plasmas, higher total radiated energy fraction seems to come along with higher toroidal peaking.

- Radiated energy fraction includes thermal ($W_{th}$) and magnetic ($W_{mag}$) stored energy; calculated from step change in 2-pi bolometer foil resistance.
- If energy is being radiated (as opposed to being conducted to solid surfaces), it is doing so asymmetrically.
In lower-single-null diverted plasmas, toroidal radiation peaking increases with safety factor (toroidal field)

- Scan toroidal field from 4.0 to 7.0 T at constant plasma current (750 kA) in order to keep plasma stored poloidal field energy constant
- Each shot repeated twice for statistics
- Variation with identical target plasma (as observed previously)
- In general, TPF higher and then saturates or rolls over with increasing safety factor (toroidal field)
Summary of results from scans

1. For LSN diverted plasmas (low power L-mode, high-power I-mode) – **TPF maximized for single-jet shots and for two jets with synchronous timing**;
2. For inner-wall limited plasmas (low power L-mode), TPF decreases as plasma elongation increases;
3. For LSN diverted plasmas (low-power L-mode), **TPF increases (and then saturates) as safety factor increases** at constant current.

What is the common thread that ties these observations together?
There is a clear relationship between the gas jet stagger time and the growth rate of the $n=1$ MHD mode in the pre-TQ phase.

- Firing two gas jets with synchronous timing leads to fast mode growth rate (low growth time), and high TPF in thermal quench flash.
- For two-jet shots, faster growth = higher asymmetry in TQ flash:
  - Mode has less time to transport impurities?
- Lowest TPF (most symmetric) when F-jet (closer to X-point) hits plasma approximately 1 ms before B-jet.
- Inconsistent with previous results (G. Olynyk APS 2010) – still being investigated.

![Graph showing the relationship between gas jet stagger time and n=1 growth rate](image-url)
Scanning safety factor (LSN) allows us to isolate the relationship between $n=1$ growth rate and TPF.

- All of these shots had same current (750 kA) and line-average electron density ($<n_e> = 1.55-1.60 \times 10^{20} \text{ m}^{-3}$)
- Toroidal field 4.1 T, 5.0 T, 6.0 T, 6.9 T
- Clear rolloff in behavior at highest safety factor (highest toroidal field) on both $n=1$ growth rate and TPF
A rotating radiation peaking feature is observed in the current quench of some rapid shutdowns, rotating opposite to the direction of plasma current (and field). Radiation peaking during the CQ has an \( n=1 \) character (single peak per toroidal transit) and appears to be rotating at 2.4 kHz. Same fundamental toroidal mode number and rotation frequency as the halo current peaking observed in the current quench of unmitigated Alcator C-Mod disruptions. Granetz et al. 1996, Nucl. Fus. 36(5), 545.
In NIMROD extended MHD simulations (V.A. Izzo), radiation peaks where 1/1 mode flow **expels hot core toward impurities** on LFS.

Location where 1/1 flow mixes impurities toward core is 180 degrees away from radiation peak.

Radiation is peaked here...

...not here

\[ n_{\text{Ne,ion}} (\text{m}^{-3}) \]

\[ T_e (\text{eV}) \]

\[ \text{TPF} = 2.1 \]

\[ \equiv \text{Maximum } P_{\text{rad}} / \text{Average } P_{\text{rad}} \]

n=1 flow at 22.5°

PI2.00003 → 3:00 pm (right after this talk!)
All of these observations provide evidence that the toroidal radiation asymmetry is controlled by low-\textit{n} MHD modes

1. Toroidal radiation peaking in flash of thermal quench correlates with growth rate of \textit{n}=1 MHD mode (inversely with growth \textit{time}) such that faster \textit{n}=1 growth means more toroidally asymmetric thermal quench flash.
   - True for single-jet rapid shutdowns with a scan of safety factor, \textbf{and}
   - True for two-jet rapid shutdowns with a scan of gas jet stagger time.

2. In inner-wall limited plasmas, toroidal radiation peaking correlates with \underline{overall radiated energy fraction}, indicating that whatever is causing the stored energy to be radiated, is doing it asymmetrically.

3. Observe rotating radiation peaking in \textbf{current quench} of some shots, at similar frequency and same direction as previously observed \textit{n}=1 halo current peaking.

4. Extended MHD simulations (NIMROD) by V.A. Izzo indicate that radiation asymmetry during thermal quench is driven by phase of (1,1) mode, \textbf{not} by location of injected gas.
These observations and simulations indicate that simply adding more gas jets to ITER will not reduce TPF to unity.

- Scaling to larger device, current quench duration in gas jet rapid shutdowns $\sim L/\text{Resistance} \sim R^2$, thus $P/A \sim R^{-1}$
- Unclear what happens to thermal quench duration (ITPA MDC-1), if TQ duration invariant with size then $P/A \sim R$ in thermal quench, thus thermal quench is most important factor for wall melt in ITER
- Redundancy dictates >1 gas jet in ITER as a bare minimum
- However, even with unlimited gas jets, it is likely not possible to reduce toroidal peaking to zero in thermal quench.

- Link between $n=1$ MHD mode and radiation peaking suggests that one course of action might be to cause the mode to rotate quickly during the TQ (one rotation in C-Mod TQ $\sim 8$ kHz rotation), so light shines evenly when averaged over TQ.
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Additional information
Rapid shutdown by massive noble gas injection is a leading candidate for disruption mitigation on ITER.

- A disruption is a general term for a sudden termination of a plasma discharge.
- They can have a variety of causes, each relating to the crossing of a stability limit:
  - **MHD stability** – $\beta$ limit, (2,1) internal kink ($q$ limit)
  - **Radiative instability** – density (Greenwald) limit, impurity injection (“UFO”)
  - **Locked mode** – plasma mode interacts with field asymmetries
- Disruptions have the potential to damage plasma-facing components on large machines (ITER).
- **A rapid shutdown system** is one component of a disruption mitigation (DM) system. DM also includes real-time stability calculations, disruption prediction, disruption avoidance, and runaway electron mitigation. “Disruption mitigation” and “rapid shutdown” are often used interchangeably.

### Flowchart:

1. **Real-time stability calculations**
2. Decision: Can we avoid a disruption?
   - Yes: **Disruption avoidance**
     - Real-time adjustment of plasma parameters to avoid crossing stability limits
   - No: **Rapid shutdown**
3. **Rapid shutdown**
4. **Runaway mitigation**
5. **Disruption and runaway mitigation**

- **Disruption avoidance**: Pre-shot planning “open loop”

- **Work on Alcator C-Mod** focuses on the rapid shutdown aspect of disruption mitigation.
The peak flow rates on the two jets have been adjusted to be within 15% of each other, but only the early phase matters.

Used this one
AXUV photodiodes do not have a flat spectral sensitivity, which complicates radiated power measurements during the TQ.

- DIII-D DISRAD diagnostic compared plasma radiation through different filters to determine an effective diode sensitivity in flattop (0.275 A/W) and during the CQ (0.12 A/W) Gray et al. (2004) Rev. Sci. Instrum. 75, 376

- During the thermal quench – plasma is cooling and charge states changing.
Why do we believe that toroidal asymmetry data from diodes equals actual toroidal radiation asymmetry?

• For this not to be true, you would have to have significant toroidal variation not only in radiated power, but also in the **spectrum** of that power

• Recombination rates dependent on density which means that charge state density at different toroidal locations could be different – but *temperature* will equilibrate fast:

\[
\dot{q} = -\kappa \nabla T_e \\
\kappa = \kappa_0 T_e^{5/2} \\
\kappa_0 = 2000 \text{ W m}^{-1} \text{ eV}^{-7/2}
\]

• At 100 eV, \( \kappa = 2 \times 10^8 \text{ W m}^{-1} \text{ eV}^{-1} = 1.25 \times 10^{27} \text{ m}^{-1} \text{ s}^{-1} \)

• Equilibration time \( \tau \sim 2n(\pi R)^2/\kappa = 4 \mu\text{s} \ll \tau_{\text{TQ}} \)

• Indicates that spectrum will be similar at different toroidal locations even through TQ.
Thomson scattering data indicate that the plasma is cold during current rearrangement phase.

**Best estimate**

$\sim 350$ eV

**1-σ range** 150–1500 eV

- Use ratio of innermost two spectral channels on Thomson scattering system (channels 2, 3)
- Channels 0, 1 see no signal to within (large) error bars
- Two-point fit gives temperature if you have floor on density
- FRCECE radiometer in cutoff means density > $5.6 \times 10^{20}$ m$^{-3}$
A variety of experiments were carried out in the FY2012 C-Mod campaign to explore rapid shutdowns with one and two gas jets.

1. Scan of *gas jet stagger time* (two jets) in **1 MW ICRF-heated L-modes**, normal field, LSN diverted configuration, stored energy 43–52 kJ

2. Scan of *gas jet stagger time* (two jets) in **3.6 MW ICRF-heated I-modes**, reverse field, LSN diverted configuration, stored energy 120–130 kJ

3. Scan of *stored energy* in reverse field, LSN diverted configuration, L-mode at low power going into I-mode at higher power (single gas jet)

4. Scan of *plasma elongation* in inner-wall limited configuration, Ohmic, constant current and safety factor (single jet)

5. Scan of *safety factor* at constant current, normal field, Ohmic, LSN diverted configuration (single jet)
Relationship between six-diode (DMBolo) and chord-integrated (AXA/AXJ) asymmetry is not clear.

- Previous work (Olynyk APS 2010) had indicated that AXA/AXJ asymmetry increased with \( n=1 \) growth time for shutdowns with single gas jet (B-jet).
- New results suggest opposite, with scans of elongation and gas jet stagger time.
- Possible that growth time of \( n=1 \) mode is not actually cause of TPF but rather is another result of some other property of the MHD.
- Correlation different between single-jet and multiple-jet scans?
For the scan of elongation (inner-wall limited configuration), no relationship to $n=1$ growth rate is seen.

- All of these shots had same current (750 kA) and line-average electron density ($\langle n_e \rangle = 1.45 - 1.60 \times 10^{20} \text{ m}^{-3}$)
- Toroidal field 6.9, 6.3, 5.2, 4.3, 4.0 T
- Slowest growth for highly elongated plasmas (almost diverted), fastest growth for low-elongation circular (diamond-shaped) plasmas, but toroidal peaking factor doesn’t seem to correlate.
These observations suggest some next steps that should be taken to further understand the physics of rapid shutdowns.

- Further extended MHD simulations should be carried out in NIMROD:
  - Inject impurities in $n=2$ fundamental pattern (~ two toroidal gas jets)
  - Add stagger time to impurity injection (try to reproduce “sweet spot”)
  - Inner-wall limited configuration: vary elongation ($\kappa$) and safety factor ($q$)
  - These simulations will be carried out as part of Olynyk thesis research

- In general, there is a need for plasma diagnostics that can operate in disruptions:
  - Through the thermal quench if possible – plasma temperature rapidly changing
  - Fast time-resolution spectroscopy (streak camera?) – lots of light available! – would give inputs to diode sensitivity curve to use silicon photodiodes more accurately as bolometers
  - Foil bolometry (flat spectral sensitivity) with “knife shutter” to expose a series of bolometers would give most reliable time-resolved $P_{rad}$ data.

- Most importantly, if we care about toroidal asymmetry in emitted radiation, we need diagnostics that are set up to observe toroidally asymmetric plasma.
  - Most diagnostics assume toroidally symmetric plasma, or else observe poloidal plane at one single toroidal location.
  - Combined with spectroscopic data, a series of wall-mounted diode arrays looking toroidally and poloidally will be necessary to fully characterize the radiation pattern during the thermal quench phase of gas jet rapid shutdowns.