Subject: Investigation of Transient Events & Pedestal Stability in I-Mode


Group: Pedestal/Edge

Date: July 30, 2015

1 Purpose of experiments

Include immediate goal of the experiments, scientific importance and/or programatic 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 purpose of this experiment is to further examine the intermittent ELMs or ELM-like events observed in I-mode operation. These transients, which were initially identified as ELMs based on the characteristic $H_\alpha$ spikes observed in the discharges, are of uncertain origin and do not exist within a well-defined parameter space – to date, the most consistent observation of these event is in I-mode operation at reduced field ($\sim 4.5$ T). Initial studies of these events suggest that they are not true, instability-driven ELMs, based on the lack of an observed pedestal crash and modeled stability against the modes associated with the ELM trigger [1, 2]. Moreover, initial observations of the divertor particle flux in these events are distinct from the typical observation in conventional ELMs, though diagnostic coverage was limited in these cases. This experiment will generate a broader dataset of I-modes containing these transient events, with dedicated pedestal/edge diagnostic coverage geared towards a more thorough characterization of these events.

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).

The I-mode [3] regime is typically described as naturally free of ELMs, among its other benefits as a potentially reactor-relevant regime. However, under some circumstances small ($< 1\%$ drop in plasma stored energy), intermittent events resembling transient ELMs may occur. The conditions in which these events may arise are not well-understood – the most consistent predictor is operation at reduced ($\sim 4.5$ T) field, although this does not firmly delineate the parameter range in which the events occur (that is, they may occur even at normal field, and do not appear consistently even at reduced field). Clearly, more study is needed to characterize these events and solidify the parameter range in which I-mode can be said to be “naturally ELM-free.”

Notably, the behavior in most of these events appears distinct from that in conventional type-I ELMs. Fundamentally, ELMs are characterized by three observables:
Figure 1 – traces of density, core and edge $T_e$, and edge recycling light in ELMs/ELM candidates in H-mode (left) and I-mode (right). In the H-mode case, ELMs are regular and distinct from the sawtooth cycle, and exhibit characteristic pedestal temperature crashes. In I-mode, however, the $H_\alpha$ spikes are tied to the sawtooth heat pulse, and do not appear to exhibit a negative pedestal perturbation.

1. a burst of ionization light at the edge, visible as an $H_\alpha$ spike

2. “explosive” crash in pedestal temperature, pressure, and stored energy

3. unstable fluctuation leading up to ELM crash (peeling-ballooning MHD instability, magnetic precursor, limiting turbulence)

In I-mode, the candidate ELMs are identified based on item (1) only – however, upon examination of the other two characteristics distinctions appear. In most cases, the ELM candidate in I-mode is tied to the sawtooth heat pulse reaching the pedestal, rather than existing in an independent cycle – this is potentially due simply to the sawtooth inversion radius moving radially outward in the reduced-field cases. Moreover, the events often do not exhibit the characteristic negative pedestal perturbation expected for an ELM (see Fig. 1). When examined numerically for stability against both the peeling-ballooning MHD and limiting kinetic-ballooning turbulence associated with the ELM trigger, I-mode cases are consistently found to be stable, even accounting for the perturbation of the pedestal due to the sawtooth heat pulse [4] (see Fig. 2).

In a minority of cases, the events in I-mode do exhibit the characteristic pedestal crash of an ELM (see Fig. 3). However, in these cases the stationary pedestal structure around these isolated transient events is still evidently stable against the MHD and turbulent modes associated with the ELM trigger, implicating a transient perturbation to the pedestal in triggering the ELM (for example, an injection of material could locally modify the density and collisionality of the pedestal, significantly modifying the pedestal in stability space).

Examination of the divertor Langmuir probes revealed details not seen in the $H_\alpha$ traces (Fig. 4): The I-mode ELMs occurred most often during transitions from L- to I-mode where the electron temperature pedestal slowly built up. Early in this transition there was a coherent oscillation at about the same frequency ($\sim 10$ kHz) of the Geodesic Acoustic Mode (GAM, which Cziegler found to exist in all C-Mod I-mode plasmas he examined [5]) although this has not been definitively identified as such. Mid-way through
**Figure 2** – ELITE and BALOO stability modeling for an I-mode exhibiting ELM candidates, with characteristic traces shown at right. Candidate events are timed with the sawtooth heat pulse, and do not exhibit an “explosive” pedestal crash. Both numerical codes find the pedestal to be stable.

**Figure 3** – ELITE and BALOO stability modeling for an I-mode exhibiting ELM candidates, with characteristic traces shown at right. The event in this case does exhibit the classic signs of an ELM (pedestal crash independent of the sawtooth cycle) but is modeled to be stable in the stationary state.
Figure 4 – Traces of inner and outer divertor Langmuir probe current, divertor \(H_\alpha\), and edge \(T_e\) through the early, mid, and late parts of a slow transition from L- to I-mode. Early in the transition there is coherent fluctuation at about the GAM frequency (~10 kHz). Mid-way through the transition there are regular bursts along with the coherent fluctuation. Late in the transition the burst frequency decreases and becomes less regular.

the transition a periodic burst of particle flux is measured with the Langmuir probes, coexisting with the coherent oscillations. These bursts were typically too small to be seen on the \(H_\alpha\) trace. Late in the transition the bursts decreased in frequency, increased in amplitude, and were now visible on the \(H_\alpha\) trace.

This type of phenomena—bursts of particle flux, first regular in frequency and then decreasing in frequency and increasing in amplitude—is reminiscent of slow transitions from L- to H-mode seen elsewhere [6]. There it was identified as a limit-cycle-like oscillation of turbulence and shearing flows. The past experiments on C-Mod exhibiting these types of events did not have GPI. Thus one large motivating factor for exploring I-mode plasmas with these ELM- or LCO-like bursts in more detail is to see what GPI can tell us about the edge plasma turbulence and flows during these events.

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.

The approach for this experiment is somewhat exploratory, given that the conditions under which these events occur are not entirely well-known. We will target the three key parameters most associated with the events/fluctuations in I-mode:

1. Low-field operation associated with transients
2. slow L-I transitions to better capture edge fluctuations during the transition
3. edge safety factor and temperature controlling GAM damping in the edge

To this end, all shots will be executed at 4.3 T with an L-mode target density of \(n_{\text{L04}} \sim 0.8 \times 10^{20} \text{ m}^{-2}\), consistent with the target discharge 1120830007. ICRF heating will be swept steadily from 2 – 3 and 3 – 4 MW to induce a slow L-I transition, allowing the observation of transient fluctuations during the
transition, as well as their modification by heating power or edge temperature. The power sweep will also modify the pedestal temperature, scanning the GAM damping rate \( \gamma \sim \nu_{ii} \sim T_i^{-3/2} \). Lastly, we will scan the plasma current from 0.6 – 1.1 MA, scanning the edge safety factor at fixed field \( (q_{95} \text{ from } \sim 2.9 – 5.4) \) again providing a scan of the GAM damping rate \( \gamma \sim 1/q \sim I_p \). Shots successfully triggering the desired transients may be repeated as necessary to build suitable statistical coverage of the events, both during the L-I transition and in steady I-modes.

This run should be in reversed-field, such that LSN plasmas with the \( \nabla B \)-drift direction is away from the active x-point. This allows for a larger access window to I-mode plasmas while having the better-diagnosed lower-divertor as the active divertor.

4 Resources

4.1 Machine and plasma parameters

Give values or range for all of the following:

<table>
<thead>
<tr>
<th>Toroidal field</th>
<th>4.3 T (reversed-field)</th>
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<tbody>
<tr>
<td>Plasma current</td>
<td>0.6 – 1.1 MA</td>
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<tr>
<td>Working gas species</td>
<td>Deuterium (D(_2))</td>
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<tr>
<td>Density</td>
<td>( n_{i04} \sim 0.8 \times 10^{20} \text{ m}^{-2} ) (L-mode target)</td>
</tr>
<tr>
<td>Equilibrium configuration</td>
<td>Reference shot 1120830007</td>
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<tr>
<td>(if possible, refer to database equilibria)</td>
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<tr>
<td>Pulse length, typical current and density waveforms, etc.</td>
<td>As in 1120830007. Aim for I-mode. Steady linear ramp of ICRF power from 2 – 3 and 3 – 4 MW, 0.5 – 1.5 s.</td>
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<tr>
<td>(refer to database or sketch desired waveforms)</td>
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<tr>
<td>Boronization required?</td>
<td>Boronization within the previous two weeks desired – I-mode experiment should be at least 3 days removed from last boronization.</td>
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<tr>
<td>(if yes, specify whether overnight or between-shot, how recently needed, and any special conditions.)</td>
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4.2 Auxiliary systems

List requirements for the following Alcator C-Mod auxiliary systems:
ICRF (power, pulse length, phasing) Request up to 4 MW, in linear ramps from 2 – 3 and 3 – 4 MW. Start ramp at 0.5 s, run to 1.5 s.

LHCD (power, pulse length, phasing) Not required

Pellet injection (list species) N/A

Impurity injection (laser blow-off) Not required. May piggyback.

Diagnostic neutral beam Not required.

Special gas puffing Neon puffing for impurity seeding. Argon (Ar) available for HiReX SR. Deuterium (D2) puffing for CXRS. Helium puffing for GPI.

Cryopump yes

Non-axisymmetric coils (list connections and current) Not required

Other None

4.3 Diagnostics

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

• Core and edge Thomson Scattering: edge fibers arranged for shape as in reference shot 1120830007
• Divertor Langmuir probe sweeps optimized to observe fluctuations, reciprocating probes as compatible with plasma and RF conditions.
• CXRS \( T_i, \ E_r \) profiles / \( E \times B \) shearing rate
• GPI turbulence spectra, mid-plane and x-point views if possible
• HiReX SR \( T_i \) (incl. Ar puffing)
• ECE \( T_e \), arranged for reduced-field operation
• O-mode reflectometer for edge \( \tilde{n}_e \)

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.

One full run day is sufficient to complete the targets in this experiment. All discharges will be at 4.3 T, in reversed field configuration. A boronization within the previous two weeks is desirable – however, this run should be at least three days removed from the previous boronization for density control purposes.

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.
All shots will be at 4.3 T, shape as in reference shot 1120830007. Density set at L-mode target of $n_{\text{L-mode}} \sim 8 \times 10^{19} \text{ m}^{-2}$ ($\bar{n}_e \sim 1.25 \times 10^{20} \text{ m}^{-3}$) (this may be adjusted for the low-current set points if the Greenwald fraction is too high for I-mode). The plasma current will be scanned from 0.6 – 1.1 MA in steps of 100 kA (i.e., current at 600, 700, 800, 900, 1000, 1100 kA). At each current point, repeat with two distinct RF programs – first, a linear ramp 0.5 – 1.5 s from 2 – 3 MW, second a similar linear ramp from 3 – 4 MW. After each current/RF power pairing, the shot will be repeated with flat-top RF power step(s) at power levels of interest based on the results from the preceding RF ramp.

**total:** 2× power scans 6× current points 2× RF flat-top repeats = 24 shots

allowing leeway for further exploration of particularly successful set points.

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.*

This experiment will generate a more thoroughly-diagnosed dataset spanning a broader, more systematic parameter range containing transient fluctuations and putative ELMs in I-mode. Previously, study of these events has proven difficult due to their rarity, and the uncharacterized parameter space in which they occur. We aim to better develop the understanding of fluctuations and ELM stability in the L-I transition and stationary I-mode, including the necessary conditions for which these events may be suppressed – for example, further exploration of successful discharges might involve raising the field at fixed $q_{95}$ to eliminate the transients. These experiments will lead to at least one publication.
References


