1. Purpose of Experiments

The goal of this mini-proposal is to optimize sawtooth stabilization. Study of this topic in C-Mod was suggested by J. Hosea at various C-Mod reviews. This mini-proposal was developed in collaboration with F. Bombarda, S. Migliuolo, C. K. Phillips, and J. R. Wilson.

2. Background

Substantial data on sawteeth are already available from previous experiments. Lengthening of the sawtooth period has been observed routinely with ICRF heating. However, a completely stabilized sawtooth, seen in other tokamaks, has not yet been observed in C-Mod. This may be because only very limited data exist in regimes favoring fast ion stabilization of sawteeth. A short dedicated run time is necessary to explore such a regime.

Bombarda and Migliuolo have analyzed approximately twenty-five C-Mod shots and used the experimental data (density and temperature profiles, in particular) to compare the properties of sawteeth observed in C-MOD with two-fluid theory [1]. Before describing details of the analysis, the following should be noted:

1. We have no information concerning magnetic shear at the $q = 1$ radius, or for that matter, the $q(r)$ profile. This is a major source of uncertainty in this work.

2. The estimate for the ideal-MHD instability parameter is carried out in the simplest of limits [2]: circular, concentric flux surfaces. This may actually be less of a problem than suspected initially. Recent calculations [P. Detragiache, unpublished, 1996] indicate that this possibly introduces an error of 10% or less in the final answer since, as
far as the theoretical model is concerned, it is the shaping at the \( q = 1 \) surface that is involved in \( \delta W_{MHD} \) and, apparently, neither ellipticity nor triangularity propagate much to the \( q = 1 \) surface, estimated to be located at \( r_1/a \sim 1/4–1/3 \).

3. The two-fluid theory does not include the effect of finite Larmor radius, \( \rho_s/r_1 \) (though it includes finite diamagnetic frequency), or collisionless skin depth. Migliuolo is currently looking at these and preliminary results indicate that electrical resistivity (which is in the model) dominates over the effect of the collisionless skin depth and its contribution is often larger than \( \rho_s/r_1 \).

Keeping in mind these limitations, Migliuolo and Bombarda find that all shots analyzed so far are subject to resistive sawteeth, \( \delta W_{MHD} > 0 \). There are five shots for which sawteeth are largely absent [only a weak and irregular oscillation is observed on the ECE polychromator] and they occur in a region of parameter space that either coincides or is near the theoretically predicted [3] region of stability for resistive \( m = 1 \) modes.

One shot is particularly interesting, 960214035 (around \( t = 0.70–0.8 \) sec). The sawteeth in this shot are very long [Migliuolo called them “monsters” in analogy with those seen in JET]. That shot, along with another (960116025) are those for which the present model predicts that the plasma should be unstable to an IDEAL \( m = 1 \) mode. However, the characteristics of the oscillations are those of resistive modes (i.e., the inferred radial displacement is maximum at the \( q = 1 \) radius and decreases inward). Since these are RF heated plasmas, it is natural to ask whether energetic ions may play a stabilizing role. Migliuolo has computed the standard [4] expression for the fast ion contribution to the overall \( \delta W \) (MHD+kinetic) as follows:

1. A simulation for shot 960214035 has been performed using the FPPRF code at a minority concentration of 5%. Since the overall effect is proportional to the volume average of the fast ion beta (within the \( q \leq 1 \) volume), the result may not be too sensitive to the minority concentration (smaller concentrations will probably mean that fewer minority ions will acquire a comparatively larger energy on a per-ion basis). The simulation indicates that high energy tails of magnetically trapped fast ions are produced in the region \( r/a \leq 0.2 \) with energies up to 100 keV [this energy may be an over-estimate owing to mixing by sawteeth].

2. The fast ion distribution is modelled, simply, by a narrow slice in \( V_\parallel - V_\perp \) space (essentially the product of two Heavyside functions with pitch angle as the variable). Only those particles that are contained within the “slice” are counted toward the \( \delta W_{fast} \). A gaussian dependence in energy and radius is found to match the simulation results reasonably and is used to compute \( \delta W_{fast} \) (which involves integrals over energy, pitch angle, and radius).

3. Keeping all other things constant, it is found that a maximum energy (of the minority ions) of
a) 100 keV is sufficient to strongly stabilize the $m = 1$ mode. This would mean that the eventual crash may be related to the temporal increase in the size of the $q \leq 1$ region (this was seen to be the case in JET).

b) 80 keV is sufficient to make the resistive $m = 1$ mode marginally stable (the ideal mode is stable). This would delay the crash for a while until the plasma beta increase further.

c) 60 keV is sufficient to make the ideal mode stable ($\delta W_{MHD} + \delta W_{fast} = 0$). The resistive mode is then unstable (as with other shots) and it remains to be explained why the sawteeth are different here.

These results are far from conclusive, but they point out intriguing possibilities for the generation of long period sawteeth (or possibly altogether sawtooth-free intervals) in Alcator C-MOD.

3. Approach

Describe the methodology to be employed; explain the rationale for the choice of parameters, etc. 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.

Theoretically fast ion stabilization favors high $\beta_p$ of the fast ions (energy of order 100 keV) with the pressure gradient of the fast ions inside the $q = 1$ surface. A higher-than-normal minority concentration at low density is a regime of interest not yet explored. Results from other experiments indicate that the best H concentration is somewhat higher than our normal operating range (5–10% instead of the usual < 2%). A high minority concentration (which produces less energetic minority ions) helps localize the absorption along the major radius, whereas higher density (which results in better wave focusing) helps localize the absorption vertically. However, both have the effect of reducing the minority ion energy.

The approach is to accumulate more data piggy-backing on other experiments. These data should be carefully analyzed to establish trends. A regime most likely to produce sawtooth stabilization should be identified. A brief scan in H minority concentration (upward) will be performed in the regime identified. Another key parameter is the size of the $q = 1$ radius. A brief scan in plasma current will be performed at higher H concentrations.

4. Resources

4.1 Machine and Plasma Parameters

Give values or range for:

**Toroidal Field**: 5.3 T

**Plasma Current**: 0.6–1.2 MA

**Working gas species**: D (majority) and H (variable concentration)
Density: \( \bar{n}_e = 1 - 1.5 \times 10^{20} \text{ m}^{-3} \) (target value before H-mode)

Equilibrium configuration (if possible, refer to database equilibria): Lower single-null, 1 cm outer gap

Pulse length, typical current & density waveforms, etc. Refer to database or sketch desired waveforms: current flat-top of at least 0.4 sec.

### 4.2 Auxiliary Systems

**RF Power, pulse length, phasing**: Full power

**Pellet Injection (species)**: none

**Impurity blow-off injection**: none

**Special gas puffing**: D/H mixture

**Other**:

### 4.3 Diagnostics

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

All available diagnostics. Spectroscopic determination of D/H ratio (U. Md.). ECE polychromator, soft X-ray arrays.

### 4.4 Neutron Budget

Estimate the neutron dose rate at the site boundary. Give basis for estimate. (Once some experience has been gained a standard formula will be provided for estimating dose rates.)

Less than \( 10^{13} \) per shot.

### 5. Experimental Plan

#### 5.1 Run sequence plan

Specify total number of runs required, and any special requirements, such as consecutive days, no Monday runs, extended run period (10 hours maximum), etc.

6 shots.

#### 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.

A shot-by-shot minority concentration scan \( (n_H/n_e = 0.05, 0.10) \) will be performed under the condition producing the longest sawtooth period (assuming the optimum density has been identified). Repeat the concentration scan (5 and 10%) at little lower and a little higher current (by about 20% in each direction).

The RF power will be fixed at full power.
6. Anticipated Results

Discuss possible experimental outcomes and implications. Indicate if the program 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.

Demonstration of sawtooth stabilization at C-Mod parameters (higher density and collisionality), and possibly improved performance (higher peak temperatures, higher fusion reactivity, higher confinement).

7. References

Include references both to external and internal literature or communications which bear on this proposal. See Section 2.