1. Purpose of Experiments

The purpose of these experiments is to perform a focused study regarding the apparent poloidal asymmetry of the Weakly Coherent Mode (WCM) associated with the I-mode confinement regime \[1,2\]. In particular, the study seeks to

- recreate a strong WCM detectable on the Mirnov coil arrays, which have been augmented with additional coils;
- corroborate with phase contrast imaging (PCI), whose chords strike the last closed flux surface (LCFS) at positions above and below the midplane; and
- examine whether pulsing the lower hybrid (LH) antenna has an effect on the poloidal localization of the WCM; while
Figure 1: Observation of poloidal asymmetry of WCM using Mirnov coil data from 2010 and 2011 [3]. (a) In a forward field discharge (1100204019), the WCM appears to be displaced above the midplane, while (b) in reverse field (1110215017), it is displaced below the midplane. The direction of displacement follows that of the electron diamagnetic drift velocity.

- measuring the edge potential profile via charge exchange recombination spectroscopy (CXRS) and/or the Mirror Langmuir Probe (MLP).

As the Mirnov coils and PCI diagnostics are passive, we envision these experiments to be best run “piggybacking” on runs dedicated to exploring the effect of the LH antenna on I-mode and the WCM, or studying the WCM with the MLP, since the associated low-RF-power plasmas allow for smaller gaps between the plasma and the Mirnov coils.

2. Background

Discuss Physics basis of the proposed research, prior results at Alcator or elsewhere, and any related work being carried out separately.

In April, 2011, Dennis Whyte identified a possible poloidal asymmetry in the WCM [3, 4]. Using a Mirnov coil data set from 2010 and 2011, Dennis found that, for reverse field discharges, the WCM signal was more prominent on coils located below the midplane, while greatly attenuated or completely suppressed on coils above the midplane. In forward field discharges, the WCM appeared to be displaced above the midplane. The direction of these observed displacements aligned with the electron diamagnetic drift direction. Dennis presented these results at a C-Mod weekly science meeting; his analysis is recapitulated in Figure 1.
Figure 2: Figures 2 and 3 of [5]. Demonstration of displacement from outer midplane for ballooning microinstability model of Dickinson et al. (a) “Isolated” modes tend to appear at the outer midplane, while (b) “general” modes may be displaced from the outer midplane, usually centered at at $\theta = \pm \frac{\pi}{2}$ radians. (c,d) Application of flow shear results in a smooth transition from isolated to general modes.

Dennis referenced a theoretical analysis summarized by H.R. Wilson, which has also been recorded in a recent paper by D. Dickinson et al. [5]. The analysis examines a ballooning mode model in one and two dimensions which is appropriate to core ITG turbulence. It shows that two qualitatively different eigenmode solutions appear: the “isolated” mode, determined from assuming the mode to be localized at the location which maximizes the growth rate, and the “general” mode, whose growth rate is effectively averaged over the poloidal angle, $\theta$, in the mode surface. The authors argue that special conditions are needed to satisfy the conditions in which an isolated mode is allowed, and that typical profiles usually do not permit such modes. In these cases, the “general” modes persist, but with higher critical gradients and lower growth rates. While the isolated mode usually sits at the outboard midplane, the general mode is typically centered at the top or bottom of the circular cross-section plasma under study. The authors further explain that

- in the presence of (toroidal) flow shear, the isolated mode transitions smoothly into the general mode, since the flow shear tends to disallow the isolated mode by removing the stationarity location in the dispersion relation, and

- this behavior may help to explain small ELM regimes, as follows: edge profiles may be usually constrained by turbulence proceeding from general mode fluctuations, but as gradients build up, the conditions for isolated and general modes to appear may both be transiently satisfied; at this instant, the isolated mode (the canonical ballooning mode, with faster growth rate) takes over, resulting in a bursting event which relaxes the profile and returns the state to that in which general modes dominate.

These results are summarized graphically in Figure 2.
Though this study focused on ballooning modes in a core ion temperature gradient (ITG) mode regime, the authors believe that it applies generally to “microinstabilities” – those with a characteristic length scale on the order of the ion Larmor radius, $\rho_i$.

The analysis developed by Dickinson et al. references and extends earlier work by Dewar and others, which examined a one-dimensional “ballooning Schrödinger equation” (BSE) using a Wentzel-Kramers-Brillouin (WKB) approximation method, revealing “trapped” modes (also called Type I ballooning modes) restricted to particular wave number and poloidal locations around periodic maxima of the local growth rate, as well as “passing” (Type II ballooning) modes, which may be localized around any poloidal centroids. The effect of frequency shear was examined, indicating that (a) the mode spectrum remains discrete, and (b) the growth rates are reduced by shear. These results ought to be applicable to investigating the effect of flow shear.

It is known that the WCM has a high perpendicular wave number, $k_\perp \sim 1.5 \text{ cm}^{-1}$, and that it is approximately field-aligned. Moreover, the well that develops in the radial electric field during I-mode indicates strong shear in the $E \times B$ flow, though it should be noted that the well is not as deep as that which occurs in Enhanced D$_\alpha$ (EDA) H-mode. It is possible that the resultant shear leads to the partial suppression of edge turbulence, and/or a change in character of these fluctuations, transitioning from the “isolated” variety (with higher linear growth rates) to the “general” variety (with lower growth rates). If the Weakly Coherent Mode is, indeed, displaced poloidally from the outer midplane, preferring locations either above or below the midplane depending on the direction of the electron diamagnetic drift direction, it would lend support to this physical interpretation of the edge fluctuation dynamics characterizing I-mode.

Experimentally, such an asymmetry might also explain why the mode is not always observed on particular fluctuation diagnostics.

In his analysis, Dennis Whyte attempted to calibrate the relative magnitude of Mirnov coil signals by normalizing to the magnitude of the sawtooth precursor. This fluctuation, with toroidal mode number, $n = 1$, is observed on essentially all Mirnov coils, and so it is a good reference to help remove systematic differences between Mirnov coil signals. However, because the perpendicular wave number of the WCM is high, the perpendicular magnetic field fluctuation attenuates rapidly in the radial direction when moving away from the mode layer, with a reduction from the LCFS of $e^{-k_\perp \Delta r} \sim 100$ expected. Since the level of attenuation is very sensitive to the radial separation between a particular coil and the mode layer, comparison of fluctuation amplitudes between coils at different poloidal angles is complicated.

Additionally, since the WCM is believed to be approximately field-aligned and also localized near the LCFS, the wave number of the mode varies locally with poloidal angle as
the field line spacing expands near the x-point, reducing $|k_\perp|$ and the attenuation factor.

The Phase Contrast Imaging (PCI) diagnostic can also be used to discern an up-down asymmetry. PCI chords intersect the LCFS both above and below the midplane. However, the mode propagates in different major radial directions at these locations; if the propagation direction of the mode in the lab-frame is known, then the relative magnitude of the mode above and below the midplane can be ascertained by determining the magnitudes of the inward- and outward-propagating waves (in the major radial direction). However, this is subject to the caveat that PCI provides a line-integrated measurement, and the geometric path through which the beam line pierces the WCM layer varies above and below the midplane. A mask may be used to partially filter the results to promote the signal contribution above or below the midplane. This adds some ambiguity to the absolute density fluctuation calibration, though it is still possible to discern relative differences in fluctuation strength.

It should be noted, however, that Dennis applied the same analysis technique to the Quasi-Coherent Mode (QCM), and found it to be symmetric about the midplane. Since the QCM has approximately the same perpendicular wave number as the WCM, $|k_\perp| \sim 1.5 \text{ cm}^{-1}$, and is roughly field-aligned, it is a good reference case with which to compare the WCM.

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.

New diagnostic capabilities since the experiments involved in the original data set analyzed by Dennis Whyte are as follows:

- Additional digitizer channels are now available for recording Mirnov coil signals; this has increased the inventory of coils in poloidal arrays.
- Mirnov coils are now digitized at lower voltage range, reducing bit noise, as well as at a higher sampling rate.
- Timebase synchronization now allows better cross-correlation between different diagnostics; this can be used to help filter measurements above or below the midplane due to the long parallel correlation length (relative to the perpendicular correlation length).

These capabilities have been available throughout most or all of the 2014 I-mode campaign. A round of targeted experiments provide the following additional opportunities:
The WCM is often not visible on Mirnov coils; using equilibria which produced a strong WCM signal on Mirnov coils, and moreover, minimizing the outer gap, may improve signal fidelity of the magnetic fluctuations, especially for coils in poloidal arrays, which have an increased gap to the plasma.

It has been argued that the well in the radial electric field, and resultant shear in the $E \times B$ flow, is the proximate cause of a poloidal displacement of the WCM. The lower hybrid (LH) antenna may be used to modulate the radial electric field, which may, in turn, change the poloidal location of the WCM by the same shear mechanism. LH operation during I-mode is the subject of a mini-proposal by E. Marmar.

The Mirror Langmuir Probe (MLP) provides (a) an excellent constraint for equilibrium reconstruction, critical for extrapolating the fluctuation amplitude at the WCM layer from Mirnov coil measurements and (b) the possibility of locating the WCM layer and determining its width, helping to remove ambiguity in interpretation of PCI experiments, in addition to (c) detailed fluctuation measurements that will help to clarify the mode physics. Using the MLP to examine the WCM will be the subject of a forthcoming mini-proposal by B. LaBombard.

Experiments involving LH and MLP operation during I-modes are already on the agenda of the 2014 C-Mod campaign, and an analysis of WCM asymmetry may readily be performed as a “piggyback” experiment, provided a suitable target equilibrium is selected where a strong WCM signal on Mirnov coils is expected.

4. Resources

4.1 Machine and Plasma Parameters

Give values or range for:

**Toroidal Field:** $\pm (5.0 \text{ to } 6.5) \ T$

**Plasma Current:** $-(0.8 \text{ - } 1.3) \ MA$

**Working gas species:** $D_2$

**Density:** NL04 L-mode target densities $0.5 - 1.1 \times 10^{20} [\text{m}^{-2}]$ (try to stay at upper end)

**Equilibrium configuration** (if possible, refer to database equilibria): Reverse field: 1110215017 ($|B_T| = 5.8 \ T$, $|I_p| = 1.0 \ MA$); 1130515016 ($|B_T| = 5.4 \ T$, $|I_p| = 1.0 \ MA$, near double null). Forward field: 1100204019 ($|B_T| = 5.8 \ T$, $|I_p| = 1.3 \ MA$), 1100827022 ($|B_T| = 5.4 \ T$, $|I_p| = 800 \ kA$), adapt reversed-field shot near double null (e.g. 1140515012)

**Pulse length, typical current & density waveforms, etc.** Refer to database or sketch desired waveforms. See waveforms from reference discharges
4.2 Auxiliary Systems

**ICRF Power, pulse length, phasing:** ICRF 1-4 MW (as low as possible while still providing access to I-mode)

**LHCD Power, pulse length, phasing:** LHCD, amplitude modulation at 6-10 Hz with stair-stepping amplitude, 0-600 kW

**Pellet Injection (species):** None

**Impurity blow-off injection:** None

**Diagnostic Neutral Beam:** No DNB

**Special gas puffing:** GPI (D$_2$, setup during run), D$_2$ for CXRS, Ar for HIREX suite

**Cryopump:** yes

**Non-axisymmetric Coils (Connections,Current):** Standard compensation

**Boronization (previous night or between-shot):** none

**Other:** overnight ECDC with neon for CXRS; Shoelace antenna in receiver mode (note that, as of June 2014, the antenna is currently open-circuited at the winding, but still picks up an induced signal)

4.3 Diagnostics

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

**Required:** Mirnov coils, PCI, differential TCI, reflectometer, Edge Thomson, CXRS, GPI. For Mirnov coils, make sure digitizer voltage range is set to ±2.5 V or lower (to decrease bit noise for expected weak signal levels); set sampling frequency to 5 MHz, and limit data collection window from -0.05 s to 2.0 s (these are current defaults as of the preparation of this proposal).

**Desired:** HIREX Sr, calcium blowoff, edge reflectometer, polarimeter (if available), A-port scanning probe with Mirror Langmuir Probe and QCM probe head (to make sure we puncture the mode layer)

5. Experimental Plan

Both sections must be filled in.

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.

1/2-run day in forward field, 1/2-run day in reverse field; can piggyback on I-mode runs with LH and/or MLP.
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.

Same run plan for forward and reverse field runs. What follows is a suggested shot sequence which may be adapted to combine with other run plans if this experiment is carried out as piggyback. The only stringent requirement for looking at WCM poloidal asymmetries is to select a reference equilibrium in which there was a strong WCM signal on the Mirnov coils.

1. **Locked mode calibration for HIREX Sr** (1-2 shots)

2. **Reference** – Bring up reference discharge and look for good WCM; scan ICRF power in steps to try to minimize power level (1-4 shots)

3. **Double-null discharge** Run a near double-null discharge so that gap between plasma and coils is nearly symmetric above and below the midplane. (1-2 shots)

4. **Find optimal RGap** – Starting from the nominal discharge, from 1.0 to 1.5 s (or otherwise over the time window in which the WCM is expected), sweep outer gap from 1.5 cm down to 0.5 cm. Identify the largest RGap (if it exists) at which the poloidal arrays of Mirnov coils pick up an adequately strong WCM signal. If the poloidal arrays of coils do not pick up the signal, abandon this line of inquiry for fear of again singeing the wall components. (1-2 shots)

5. **$q_{95}$ scan** – Perform a $q_{95}$ scan from 4 to 6 in 4 steps. (8-10 shots) by varying field. At every step, run two discharges:
   
   (a) **No LH**
   
   (b) **LH Pulses** at maximum RGap for which poloidal Mirnov array picks up WCM, operate LH antenna in gated, stair-step program. Pulses arranged at 6-10 Hz with 50% duty cycle. Pulse heights: \{600, 400, 200, 600, 400, 200, 600, 400, 200, 600\} kW. If possible, scan MLP through edge plasma during low-power (200 kW and/or 400 kW) LH pulse, and during plasma with no LH.

   If low on discharges, then retain only the tests with LH pulses.

**Total # discharges:** 13-18 shots (if go over shot quota, reduce $q_{95}$ scan.)
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, an ITER request, or an external database.

The objectives of this experiment are:

1. to provide a targeted survey of discharges to follow up on Dennis Whyte’s observation that the WCM might have a poloidal asymmetry,

2. to vary edge conditions in such a way as to affect this asymmetry, and

3. to provide another opportunity for a thorough characterization of the WCM using a cross-comparison of fluctuation diagnostics.

These results, combined with data from LH and MLP operation during I-mode plasmas, can be combined to give a better understanding of edge fluctuations and conditions in I-mode. Venues for presenting the results include the annual meeting of the American Physical Society Division of Plasma Physics in 2014, as well as contributed journal publications to be submitted during the 2015 fiscal year.

7. References

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


