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 second miniproposal to explore the use of the asymmetric coils. Its intention is to document the magnitude of the intrinsic field error and of the field required for locking. Since we are limited in the amount of current we can drive in the A-coils, this study proposes operation at lower plasma current and toroidal field than was used in MP 331.

2. Background

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

In summary, we have not yet discovered accurate bounds on the intrinsic and locking field values. To do so we need to get a higher ratio of applied non-axisymmetric field to intrinsic field. We can probably do it by reducing the plasma current. We can also explore a much more comprehensive set of phase angles. The rest of this section documents these statements through a quick analysis of the MP331 results. It may be skipped by the casual reader.

The A-coils have been shown to be capable of causing and of suppressing a locked mode at 1 MA plasma current, although only at one phase: \( \pm (+D_{top} - D_{bot} - J_{top} + J_{bot}) \) [1]. Two other phase conditions of the correct helicity failed to produce effects \( \pm (+D_{top} + D_{bot} - J_{top} - J_{bot}), \pm (+B_{top} - D_{bot} - G_{top} + J_{bot}) \). A configuration of the opposite, non-resonant, handedness also gave a null result.

If we interpret the studies of MP 331, 1030507, naively, assuming that the one configuration that was demonstrated to change locked modes is precisely in phase with the intrinsic error fields, we can place limits on the magnitudes of the non-axisymmetric fields. Expressing them in terms of equivalent current in the A-coils, we can ask what is the required equivalent current to lock a mode at 1 MA and \( NL04 = 1 \) (in units of \( 10^{20} \)),

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**Alcator C-MOD**

**Mini-Proposal**

**Subject:** Mode Locking Studies at Lower Current

**From:** I.H.Hutchinson, S.M.Wolfe, R.S.Granetz

**Group:** MHD

**Date:** 22 May 2003

**Approved by:** 

**Date Approved:**
and what is the intrinsic error field at 1 MA (\( I_i \))? The JET experiments\[2\] and other prior investigations have indicated that the intrinsic error field is proportional to plasma current \( I_p \), and the locking field is proportional to plasma density but scales weakly with everything else. These scalings are not obviously true in all cases, but for want of other information, let us assume here that they hold for C-Mod.

What we demonstrated on 1030507 at \( NL04 = 1 \) and 0.6 can be summarized as follows. (Values are in amps and the square brackets refer to shot numbers; we only need to assume the density scaling \( I_i \propto n_e \) for this calculation).

\[
\begin{align*}
I_i + 1800 &> I_l \\
I_i + 1300 &< I_l \\
I_i &> 0.6I_l \\
|I_i - 2300| &< 0.6I_l \\
I_i &< I_l
\end{align*}
\]

Manipulation of the inequalities to express the currents separately allows only rather loose limits to be placed on their absolute values:

\[
\begin{align*}
1950 < I_i < 8450 \\
3250 < I_l < 10250
\end{align*}
\]

These conclusions should be treated with caution because of the unverified linear density scaling assumption and the phasing assumption. Nevertheless, they suggest that we are operating presently with a power supply current limitation (2300A) that is too low to cover the range we need at 1 MA plasma current. We would like to raise the current in the coils, but to do that will require more power than we currently have. So this proposal is to use what we have but to try to operate where the current required is lower.

Since the intrinsic error field is believed by some to scale proportional to plasma current\[2\], it is proposed to explore locked modes at lower currents. Actually this scaling may be false for C-Mod if the error is primarily in the OH coil, for example. If that is so, then it is still advantageous to look at lower currents, because there will be a greater range of OH swing during the flat-top.

The different phase configurations available to us are to some degree constrained by the absence of the Bbot coil. However, an exploration of various possibilities has shown that if the (2,1) amplitude and phase are the key quantities, then we have adequate flexibility within the overall limits of the power supply. In the following table are given the (1,1) and (2,1) amplitudes and phases produced in a standard plasma at the \( q = 2 \) surface. These are now stored in the form of complex amplitudes in the MDSplus engineering tree. The phase is defined as \( \text{atan}(\Im(B_{mn}), \Re(B_{mn})) \), where \( B_{mn} \) is defined in MP 331.
Table 1. Amplitude (in tesla) and phase in radians of \((m,n)\) components arising from 1 A in each of the A-coils.

<table>
<thead>
<tr>
<th>Coil</th>
<th>((1,1)) T/A</th>
<th>Phase</th>
<th>((2,1)) T/A</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>BTOP</td>
<td>1.79e-07</td>
<td>0.151</td>
<td>6.56e-08</td>
<td>-0.496</td>
</tr>
<tr>
<td>BBOT</td>
<td>2.47e-07</td>
<td>1.118</td>
<td>8.65e-08</td>
<td>1.772</td>
</tr>
<tr>
<td>DTOP</td>
<td>2.38e-07</td>
<td>1.500</td>
<td>8.24e-08</td>
<td>0.933</td>
</tr>
<tr>
<td>DBOT</td>
<td>2.47e-07</td>
<td>2.374</td>
<td>8.65e-08</td>
<td>3.028</td>
</tr>
<tr>
<td>GTOP</td>
<td>2.38e-07</td>
<td>-2.898</td>
<td>8.24e-08</td>
<td>2.818</td>
</tr>
<tr>
<td>GBOT</td>
<td>2.47e-07</td>
<td>-2.024</td>
<td>8.65e-08</td>
<td>-1.370</td>
</tr>
<tr>
<td>JTOP</td>
<td>2.38e-07</td>
<td>-1.641</td>
<td>8.24e-08</td>
<td>-2.209</td>
</tr>
<tr>
<td>JBOT</td>
<td>2.47e-07</td>
<td>-0.767</td>
<td>8.65e-08</td>
<td>-0.113</td>
</tr>
</tbody>
</table>

For any connection, the field is the appropriate (vector) sum of the amplitudes from each coil. In table 2 are documented some choices of particular interest. The first three (A-C) are the ones of positive helicity already run. Case A is the one that is observed to be effective in causing (with negative current) or preventing (with positive) locked modes. Cases D onwards are a selection of additional possibilities. The maximum \(B_{21}\) field is determined by either the voltage limit of 300V for 4 coils in series or the current limit of 3kA for three coils.

Table 2. Various possible asymmetric coil connections, showing the mode contribution per unit current and the maximum \(B_{21}\) magnitude limited by the present power supply.

<table>
<thead>
<tr>
<th>Bt</th>
<th>Bb</th>
<th>Dt</th>
<th>Db</th>
<th>Gt</th>
<th>Gb</th>
<th>Jt</th>
<th>Jb</th>
<th>((1,1))T/A</th>
<th>Phase</th>
<th>((2,1))T/A</th>
<th>Phase</th>
<th>(B_{21}) mT</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>-1</td>
<td>1</td>
<td>4.11e-07</td>
<td>0.3255</td>
<td>2.93e-07</td>
<td>0.3957</td>
</tr>
<tr>
<td>B</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>-1</td>
<td>-1</td>
<td>8.80e-07</td>
<td>1.9461</td>
<td>1.69e-07</td>
<td>2.0230</td>
</tr>
<tr>
<td>C</td>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>-1</td>
<td>8.06e-07</td>
<td>2.8144</td>
<td>3.17e-07</td>
<td>2.8963</td>
</tr>
<tr>
<td>D</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>-1</td>
<td>-1</td>
<td>0</td>
<td>7.12e-07</td>
<td>1.3700</td>
<td>2.32e-07</td>
<td>1.2144</td>
</tr>
<tr>
<td>E</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>-1</td>
<td>-1</td>
<td>1</td>
<td>3.70e-07</td>
<td>0.9614</td>
<td>2.21e-07</td>
<td>0.5875</td>
</tr>
<tr>
<td>F</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>-1</td>
<td>0</td>
<td>-1</td>
<td>-1</td>
<td>0</td>
<td>6.15e-07</td>
<td>1.0240</td>
<td>2.66e-07</td>
<td>0.8934</td>
</tr>
<tr>
<td>G</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>-1</td>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>4.43e-07</td>
<td>0.2815</td>
<td>2.15e-07</td>
<td>0.1408</td>
</tr>
<tr>
<td>H</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>4.16e-07</td>
<td>1.8282</td>
<td>1.83e-07</td>
<td>1.8265</td>
</tr>
<tr>
<td>I</td>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3.30e-07</td>
<td>2.7093</td>
<td>2.09e-07</td>
<td>2.3929</td>
</tr>
<tr>
<td>J</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3.83e-07</td>
<td>0.2442</td>
<td>1.94e-07</td>
<td>0.1297</td>
</tr>
<tr>
<td>K</td>
<td>-1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>-1</td>
<td>6.55e-07</td>
<td>2.6226</td>
<td>2.18e-07</td>
<td>2.4839</td>
</tr>
<tr>
<td>L</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-1</td>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>6.00e-07</td>
<td>0.5361</td>
<td>1.22e-07</td>
<td>0.2265</td>
</tr>
<tr>
<td>M</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>-1</td>
<td>0</td>
<td>3.70e-07</td>
<td>0.9614</td>
<td>2.21e-07</td>
<td>0.5875</td>
</tr>
</tbody>
</table>

Cases D-I are proposed as the ones to study next, based on exploring an appropriate range of phases starting near the one observed to be effective, and giving a strong \((2,1)\) component. For notational convenience we do not regard the positive and negative signs of the same combinations as different, and we choose that combination to list that has a phase angle in the upper half-plane.

Cases J-M are of lesser priority because they give fields that are similar (J) or identical (M) to an earlier configuration (for the modes documented), or because they give lower \((2,1)\) amplitude (K,L).
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.

The general approach here is to start at about 0.6 MA and try to get a locked mode by running at low density. If one is observed, then we will attempt to suppress it using the A-coils, establishing a current threshold in the A-coils. Then we will raise the density to the point where the locked mode disappears (but not much more) and try to induce one using the A-coils. The main point is then to use different coil phasing at this operational condition that is known to be not far from locking threshold and see if we can induce a locked mode with other coil phase configurations.

If at 0.6 MA we cannot get a locked mode, even with applied fields, we will increase to 0.8 MA, and try again.

Given present experience, it does not seem likely that definitive results can be obtained with dynamic A-coil current sweeps. The intrinsic field error probably changes with time. Therefore we can’t bank on getting more than one setting per shot, till we know more.

Some of the configurations we propose use only 3 coils because the Bbot is absent. This may not be too much of a handicap because the reduction in resistance will enable us to run at the full 3kA capability of the TMX power supply. The \( n = 0 \) component that will be induced is irrelevant because it is small, non-resonant, and will be largely removed by the position feedback control. It is not certain that the other components are irrelevant, but independent exploration of that question will require more run time.

4. Resources

4.1 Machine and Plasma Parameters

Give values or range for:

- **Toroidal Field**: 4 T
- **Plasma Current**: 0.6 MA. If null result, higher.
- **Working gas species**: D
- **Density**: low.
- **Equilibrium configuration** (if possible, refer to database equilibria):
- **Pulse length, typical current & density waveforms, etc.** Refer to database or sketch desired waveforms.

4.2 Auxiliary Systems

- **RF Power, pulse length, phasing**: None
- **Pellet Injection (species)**: None
Impurity blow-off injection: None

Special gas puffing: Very little, direct puff control, not density feedback.

Other: None

4.3 Diagnostics

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

ECE and magnetics for locked mode detection. Hirex Jr would be nice but not essential.

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.)

Negligible

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.

This would be a long run day.

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.

I Establish 0.6 MA shot at 4T and low density [3 shots]

IIA If locked mode is not observed, apply A-coils with configuration -A [that is -(Dtop -Dbot -Jtop +Jbot) reinforcing intrinsic error] at maximum current and assuming we find a locked mode bisect the current till we establish reasonable accuracy on $I_A$ threshold. [5 shots]

or

IIB If locked mode is observed in I, apply A-coils with configuration +A (+Dtop -Dbot -Jtop +Jbot) (opposing the intrinsic) at maximum current and bisect to find threshold(s). (Probably we will only find the reinforcing threshold). [5 shots]

or

IIC If nothing we do generates a locked mode, raise current to 0.8 MA, and restart II, [10 shots total]

III Raise density till we are slightly above the threshold for an intrinsic locked mode. [3 shots]
IV Attempt to induce locking with full A-coil current in the following configurations. (The number of shots is 2 if the result is null, or 6 to establish the threshold if a locked mode is seen.)

D $\pm (+D_{top} -G_{bot} -J_{top})$ [2-6 shots]

E $\pm (+B_{top} -J_{top} +J_{bot})$ [2-6 shots]

F $\pm (+D_{top} -D_{bot} -G_{bot} -J_{top})$ [2-6 shots]

G $\pm (+D_{top} -D_{bot} -G_{top})$ [2-6 shots]

H $\pm (+D_{top} +G_{top} -G_{bot})$ [2-6 shots]

I $\pm (-B_{top} +G_{top} -G_{bot})$ [2-6 shots]

V If we have not generated a locked mode at a different phasing in any of (D-I), we may have time to do something else. We will revisit the 1MA, 5.3T case, try to nail down the threshold more accurately and try some of the above cases.

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.

The start of a quantitative understanding of our non-axisymmetric fields. Probably enough data for an APS presentation.

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