1. Purpose of Experiments

The purpose of this experiment is first to establish a C-Mod discharge that is dimensionally similar to one from DIII-D and measure the intrinsic toroidal rotation (i.e., that with no momentum input), and compare it to the intrinsic DIII-D rotation. The natural comparison parameter would appear to be the toroidal Mach number, M=U/v_{th}, where U is the toroidal velocity and v_{th} is the ion thermal velocity.

We will then use the available time to vary one of the four primary dimensionless parameters and measure the response in M. A goal of the experiment is to determine if M is a useful dimensionless scaling parameter, and if so, establish the dimensionless scalings of M.

In future (2006) DIII-D experiments we hope to expand this dimensionally similar database by obtaining discharges in DIII-D that correspond to selected ones from these C-Mod parameter scans.

2. Background

Addressing reactor relevant conditions regarding rotation in low momentum input discharges is an ITPA high priority research task for 2004/2005. Projecting the toroidal rotation matters for transport issues in ITER, but it will become increasingly important as final design time nears regarding the need for fast coils to suppress the resistive wall mode instability (RWM). Rotation ameliorates the RWM, possibly removing the need for stabilizing coils.
ITER will have relatively little neutral beam injection (NBI) toroidal momentum in any of the foreseen scenarios [1]. Intrinsic rotation is thus the relevant parameter to seek to extrapolate from present experiments.

Tokamak discharges exhibit intrinsic toroidal rotation, as observed in C-Mod [2], JET [3], Tore Supra [4] and DIII-D [5]. In recent years a series of experiments has been carried out on C-Mod [2]. One finding in these C-Mod experiments is an increase in $U$, in the direction of the plasma current, with plasma kinetic energy, $W$. $U$ was found to scale with $W/I_p$, where $I_p$ is the plasma current. Recently, this same scaling appears to hold in the outer region of DIII-D in ECH and Ohmic H-modes [5], where the core rotation is correlated with the ECH deposition profile and can be reversed to the counter $I_p$ direction there.

A scaling of $U$, that is $M$, with dimensionless plasma parameters would provide a model to extrapolate intrinsic rotation from present devices to ITER, as opposed to scalings using the engineering parameters mentioned above. If such a scaling does not clearly exist, it would indicate that other machine details are important in establishing the intrinsic rotation velocity, such as possibly the heating method or RF scenario, ELM details, the divertor geometry, the fraction of lost orbits in the edge region, the impurity composition, or not well matching $Z_{eff}$, and numerous other effects that could be imagined.

DIII-D discharges with dimensionless similarity to C-Mod discharges in the pedestal parameters have been obtained previously [6]. Thus a good shape match can be obtained between the two machines. However, the present database of intrinsic rotation experiments in ECH- and OH- H-modes in DIII-D was not done with this in mind. One driving consideration was to have a low L->H power threshold, which fortunately dictated a LSN shape, making it possible to come close with the C-Mod shape here. In the future we will redo the DIII-D experiment with a shape match, and similarity, to the C-Mod data obtained in this presently proposed experiment.

2A. DIII-D

One premise is that to make a cross-machine comparison we should have relatively steady state conditions in each. In DIII-D this leaves us with only a few discharges from which to select. We focused upon ECH H-modes, and most have a long ELM-free period with transient conditions and a density rise until the ECH power is cut-off from the core. Steady state is established by ELMing. For comparison with C-Mod we also ran Ohmic H-modes and these were ELMing early, providing the desired steady condition. There are also some discharges with off-axis ECH that led to early ELMing.
We plan to make the comparison of U in the core region of the discharges. The selected DIII-D Ohmic H-mode discharge case is desirable in that the rotation profile in the core is flat, leaving little ambiguity. The ECH H-mode case requires a lower density to match in C-Mod, a value essentially demonstrated [7], but has some spatial structure in the core rotation profile.

Another desirable feature of these DIII-D discharges is that in the core \( T_e \sim T_i \), as anticipated for discharges in C-Mod. In either case \( q \) on axis is close to 1 and there are relatively small sawtooth oscillations. Both of these discharges will be translated to C-Mod parameters in Section 3.

**2B. C-Mod**

Steady state conditions will presumably mean obtaining ELMing, or EDA H-mode conditions. The 80 MHz minority H ICRH scenario dictates a range of toroidal field. The dimensionless match apparently can be fit into this range [7]. We can then obtain scaling of M with some dimensionless parameters by varying \( B_T \) in this range.

However, in order to test the size scaling, \( \rho^* \), we will want a lower \( B_T \) in C-Mod, necessitating 50 MHz RF operation. This also opens the possibility of using minority \(^3\)He heating in order to have the same \( B_T \) value as used in the 80 MHz case, and test for any effect due to RF scenario.

**3. Approach**

The dimensionless parameters to match are [6]

\[
\hat{\nu} = \frac{\nu}{\sqrt{T_e}} \quad \text{collisionality (note } \frac{\nu}{\omega_b} \propto \hat{\nu} \sqrt{\beta} \sqrt{\varepsilon^{3/2}} \)
\]

\[
\hat{\beta} = \frac{n T_e}{B^2} \quad \beta
\]

\[
\hat{\rho} = \frac{\sqrt{T_e}}{a B} \quad \text{size}
\]

\[
\hat{q} = \frac{a B}{I_p} \quad q_{95}
\]

\[
\varepsilon \equiv \frac{a}{R_0}
\]

Typically \( \varepsilon \) is matched by the shape similarity and \( I_p \) is adjusted a bit to give the \( q_{95} \) match. But the existing DIII-D \( \varepsilon \) value doesn’t quite fit into C-Mod, \( \varepsilon_{\text{DIII-D}} = .61/1.71 = .36 \), whereas we nominally have for C-Mod \( \varepsilon = .22/67 = .33 \), roughly a 10% difference. (Including the effect of the region of velocity space occupied by the trapped particles gives \( \nu^* \sim \varepsilon^{-3/2} \).) The resulting difference in the true collisionality parameter will be neglected for now, and we will continue with \( \hat{\nu} \). (In the remainder of this section, the \( \hat{\cdot} \) is dropped from these parameters.)

Other primary shape defining parameters for the DIII-D set are

\[
\kappa = 1.83 \quad \text{elongation}
\]

\[
\delta_U = 0.1 \quad \text{upper triangularity}
\]

\[
\delta_L = 0.33 \quad \text{lower triangularity}
\]
The low triangularity will also presumably not be matched exactly in C-Mod [7]. The nominal shape taken for planning purposes is from C-Mod shot 1050428032.

A. Step 1 A direct similarity parameter match will be attempted in C-Mod. Table 1 gives the DIII-D parameters for the discharges selected, and the projected parameters for C-Mod. The RF heating power and gas puffing are presumably the only knobs available to try and attain the desired combination of core density and temperature.

<table>
<thead>
<tr>
<th></th>
<th>DIII-D</th>
<th>C-Mod III</th>
<th></th>
<th>DIII-D</th>
<th>C-Mod I</th>
</tr>
</thead>
<tbody>
<tr>
<td>shot</td>
<td>118190 ECH Hmode</td>
<td></td>
<td>shot</td>
<td>111154 OH Hmode</td>
<td></td>
</tr>
<tr>
<td>ν</td>
<td>1.7</td>
<td>1.7</td>
<td>ν</td>
<td>2.8</td>
<td>2.8</td>
</tr>
<tr>
<td>β</td>
<td>2.4</td>
<td>2.4</td>
<td>β</td>
<td>2.7</td>
<td>2.7</td>
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<td>ρ</td>
<td>1.1</td>
<td>1.1</td>
<td>ρ</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>q₉₅</td>
<td>4.9</td>
<td>4.9</td>
<td>q₉₅</td>
<td>3.1</td>
<td>3.1</td>
</tr>
<tr>
<td>B₀</td>
<td>1.75</td>
<td>6.27</td>
<td>B₀</td>
<td>1.75</td>
<td>6.3</td>
</tr>
<tr>
<td>n</td>
<td>5.5</td>
<td>41</td>
<td>n</td>
<td>6.9</td>
<td>53</td>
</tr>
<tr>
<td>Tₑ</td>
<td>1.4</td>
<td>2.3</td>
<td>Tₑ</td>
<td>1.2</td>
<td>2.0</td>
</tr>
<tr>
<td>Iₚ</td>
<td>1.0</td>
<td>adjust ~0.93</td>
<td>Iₚ</td>
<td>1.5</td>
<td>~1.5</td>
</tr>
</tbody>
</table>

Table 1. Scaled and real parameters for two projected C-Mod comparisons to DIII-D. The absolute and scaled units (defined above with hats) are in, and use, m, keV, 10¹⁹/m³, T, and MA.

Both of these call for essentially the same Bₜ, and it is proposed to try for both, although possibly the second set (DIII-D OH-H) may pose a challenge in C-Mod. By reducing Bₜ slightly a set can be obtained with a very slight compromise in the ρ value, but allowing the RF resonance to be moved away from the edge and reducing the density demand slightly. This may be necessary to avoid internal transport barrier (ITB) formation. These values are given in Table 2 using Bₜ = 6.0 T.

<table>
<thead>
<tr>
<th></th>
<th>DIII-D</th>
<th>C-Mod IV</th>
<th></th>
<th>DIII-D</th>
<th>C-Mod II</th>
</tr>
</thead>
<tbody>
<tr>
<td>shot</td>
<td>118190 ECH Hmode</td>
<td></td>
<td>shot</td>
<td>111154 OH Hmode</td>
<td></td>
</tr>
<tr>
<td>ν</td>
<td>1.7</td>
<td>1.7</td>
<td>ν</td>
<td>2.8</td>
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<tr>
<td>β</td>
<td>2.4</td>
<td>2.4</td>
<td>β</td>
<td>2.7</td>
<td>2.7</td>
</tr>
<tr>
<td>ρ</td>
<td>1.1</td>
<td>1.13</td>
<td>ρ</td>
<td>1.0</td>
<td>1.06</td>
</tr>
<tr>
<td>q₉₅</td>
<td>4.9</td>
<td>4.9</td>
<td>q₉₅</td>
<td>3.1</td>
<td>3.1</td>
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<tr>
<td>B₀</td>
<td>1.75</td>
<td>6.0</td>
<td>B₀</td>
<td>1.75</td>
<td>6.0</td>
</tr>
<tr>
<td>n</td>
<td>5.5</td>
<td>39</td>
<td>n</td>
<td>6.9</td>
<td>49</td>
</tr>
<tr>
<td>Tₑ</td>
<td>1.4</td>
<td>2.2</td>
<td>Tₑ</td>
<td>1.2</td>
<td>2.0</td>
</tr>
<tr>
<td>Iₚ</td>
<td>1.0</td>
<td>adjust ~0.9</td>
<td>Iₚ</td>
<td>1.5</td>
<td>~1.45</td>
</tr>
</tbody>
</table>

Table 2. Same as Table 1 with C-Mod Bₜ specified to be 6.0 T and the variance taken up in ρ.

These matched, or near-matched discharges are labeled in order of priority as presently perceived, from I-IV. Perhaps it is already clear to the experienced C-Mod physics operators that some of these are not realistic. The DIII-D OH H-mode case is ranked higher because of the flatter core rotation profile, but if M is found not to scale via
similarity it would open a question regarding the auxiliary heating mix. Hopefully each DIII-D discharge can be ‘matched’ at either 6.3, or if necessary 6.0 T.

We request 8 good discharges to obtain at least one matched DIII-D case, but hopefully both.

B. **Step 2**. Now go to a low \( B_T \) to obtain another point in \( \beta \) and in \( \nu \), with all other parameters fixed. If two cases were found in step 1, then possibly two pairs will be desired here. Nominally the low value is selected to be \( B_T = 5.3 \) T, moving the RF resonance near the axis.

How the day is going will determine whether or not one or two (if possible) DIII-D discharges is pursued in these parameters.

Figures 1 and 2 show the parametric dependences on \( B_T \) with a \( \beta \) and \( \nu \) variation for the DIII-D ECH H-mode and the OH H-mode case, respectively. The values given in Table 3 correspond to these plots.

<table>
<thead>
<tr>
<th>shot</th>
<th>DIII-D ECH H</th>
<th>C-Mod</th>
<th>DIII-D OH H</th>
<th>C-Mod</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \nu )</td>
<td>1.7</td>
<td>1.7</td>
<td>3.3</td>
<td>2.8</td>
</tr>
<tr>
<td>( \beta )</td>
<td>2.4</td>
<td>1.2</td>
<td>2.4</td>
<td>1.35</td>
</tr>
<tr>
<td>( \rho )</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.0</td>
</tr>
<tr>
<td>( q_{95} )</td>
<td>4.9</td>
<td>4.9</td>
<td>4.9</td>
<td>3.1</td>
</tr>
<tr>
<td>( B_0 )</td>
<td>1.75</td>
<td>5.3</td>
<td>5.3</td>
<td>1.75</td>
</tr>
<tr>
<td>( n )</td>
<td>5.5</td>
<td>21</td>
<td>41</td>
<td>6.9</td>
</tr>
<tr>
<td>( T_e )</td>
<td>1.4</td>
<td>1.65</td>
<td>1.65</td>
<td>1.2</td>
</tr>
<tr>
<td>( I_p )</td>
<td>1.0</td>
<td>(-0.8)</td>
<td>(-0.8)</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Table 3. Low \( B_T \) parameters for C-Mod 80 MHz heating.

For step 2, 6-10 good discharges are requested, depending upon how many of the two potential C-Mod matched case discharges in Table 3 are pursued.

C. **Step 3**. In this step we will take a different \( q \) value at \( B_T = 5.3 \), with the other scaled parameters matched to those of the DIII-D ECH H-mode discharge. Of course, now this must be taken into account to obtain the same collisionality (still ignoring the difference in \( \epsilon \)). Thus \( \nu/q \) is made equal to that for the discharge in the second column of Table 3, with the other scaled parameters remaining equal. The resulting C-Mod parameters are found to be:

\[
q_{95} = 2.5, \quad I_p \sim 1.6, \quad B_0 = 5.3, \quad n = 41, \quad T_e = 1.6
\]

This case is deemed important to obtain given the \( 1/I_p \) scaling found for \( U \) in C-Mod.

For step 3, 3 good discharges are requested.
Fig 1. DIII-D ECH H-mode target, log scales.

Fig 2. DIII-D OH H-mode target, log scales.
D. Step 4 If time permits, we will take other paths in parameter space at constant \( B_T \), leaving the RF resonance location fixed spatially. We will select from the two \( B_T \) values used in steps 1 and 2, given the results. Target parameters will be developed for each contingency. The two scans envisioned are

i) Constant \( \beta q \), with constant \( \rho \) and constant \( \nu/q \). This requires fixed \( T_e \) and it is projected to lower \( \beta \) (lower \( n \)) and raise \( q \) (lower \( I_p \)). This is important to relate to the C-Mod scaling of \( U \sim W/I_p \).

ii) Constant \( \beta/\nu \), at constant \( \rho \) and \( q \). This also requires fixed \( T_e \) and it becomes a density variation at constant \( I_p \).

For step 4, 4-8 good discharges are requested.

E. Next Phase: 50 MHz ICRF cases.

The details of these cases will be given shortly. The basic concept is for three general probes of similarity scaling in M.

First and most important is obtaining a significant difference in \( \rho \) by going to lower \( B_T \), probably \( B_T \sim 3.0 \), and matching all of the other scaled parameters. The plasma current will be low for the \( q_{95} = 4.9 \) case and obtaining the necessary density may be a problem.

Next, other cases to compare with the 80 MHz ICRF can hopefully be obtained by utilizing minority \(^3\)He heating. We would attempt a 6 T (or 6.2 T if the heating scenario allows) match to all of the parameters finally achieved, as indicated in Tables 1 and 2. Then we would attempt the same matching cases given in Table 3, at 5.3 T.

These \(^3\)He resonance discharges in comparison with steps 1 and 2 will show the effect of the heating scenario on M, if any.

4. Resources

4.1 Machine

Toroidal Field: 5.0-6.3 T \hspace{1cm} (80 MHz phase)
Plasma Current: 0.6 – 1.8 MA
Working Gas: \( D_2 \) H minority heating
Density: \( 1 - 6 \times 10^{20}/m^3 \) in the core, in steady state H-mode discharges
Equilibrium configuration: LSN. Target shot is 1050428032, with any achievable morphing for greater elongation and lower triangularities.

4.2 Auxiliary Systems

RF Power: Range of power up to maximum reliably available, 1sec pulse, heating phasing (0pi0pi?), 80 MHz for steps 1-4, 50 MHz for ‘next phase’
4.3 Diagnostics
   HIREX, Dalsa, Thomson, GPC, FSP, ASP, ISP, CHROMEX? CXRS?

5. Experimental Plan

A detailed shot plan will be developed, with contingencies specified depending upon whether one or both of the matched conditions is achieved in step 1.

The overall shot request given in Section 3, for the 80 MHz phase, is 21-29 discharges, depending upon the difficulty of achieving matched conditions etc.

7. References