Subject: Non-dimensional parameter scans in I-mode

From: S. Wolfe, A. Hubbard, J. Hughes

Group: Scenarios

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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.

We propose to carry out individual scans of non-dimensional physics parameters \( \rho^* \), \( \beta \), \( q_{95} \), and \( \nu_C \) to determine the scaling of energy confinement in the I-mode regime. This approach provides complementary information to dedicated scans of engineering parameters, e.g. \( \bar{n}_e \), \( I_p \), \( B_T \), \( P_{aux} \), and to multi-parameter database fitting. Casting the transport behavior in terms of the underlying physics parameters not only helps clarify the governing physical processes, but can provide a stronger basis for projection of the performance to future facilities (assuming that the non-dimensional parameter set and model is sufficient to represent the physics over the range of the projection). In particular, application of the constraint that the transport is governed only by the non-dimensional (scale-free) parameters implies a unique size scaling that can be inferred from the dataset of a single facility, avoiding the complications of multi-machine scaling exercises.

In the present instance, we are interested in applying the predictive results of a set of constrained experiments on C-Mod to estimate the performance of the I-mode ELM-less operating regime to high-field, compact burning plasmas such as ARC and SPARC, as well as possible implementation of this regime on ITER, as an alternative to the baseline ELMy H-mode scenario.

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).

While a number of experimental facilities, including DIII-D and ASDEX-UG, have accessed the I-mode regime, by far the most extensive database, including the widest range of absolute parameters, has been obtained on Alcator C-Mod. Walk [2] has carried out a multi-parameter linear regression on the C-Mod I-mode data and obtained a power-law scaling for the total energy confinement

\[
\tau_E(I - \text{mode}) = C I_p^{\alpha_R} B_T^{\alpha_R} \bar{n}_e^{\alpha_{\bar{n}}} P_{\text{loss}}^{\alpha_{P_{\text{loss}}}} R^{\alpha_{R}} e^{\alpha_{e}} \kappa^{\alpha_{\kappa}}
\]

\[
= (0.014 \pm 0.002) \times I_p^{0.685 \pm 0.076} B_T^{0.768 \pm 0.072} \bar{n}_e^{0.017 \pm 0.048} P_{\text{loss}}^{-0.286 \pm 0.042}
\]

where the range of \( R \), \( e \), and \( \kappa \) within the single-machine dataset was considered too small to yield a meaningful regression for \( \alpha_R \), \( \alpha_e \), and \( \alpha_{\kappa} \). The above scaling has been used by several authors to make predictions for the behavior of I-mode in future facilities, under various assumptions about the undetermined
size scaling. The basic parametric scalings have also been compared to experimental results from the larger, lower field facilities DIII-D and ASDEX-UG, which appear to give at least qualitatively consistent results. The noteworthy features of the scaling \( \alpha_P \approx -0.29 \) compared to the ITER H98(y2) scaling, \( \alpha_P \approx -0.69 \), and the strong positive scaling with current and toroidal field. Also, the fitted scaling with density is consistent with \( \alpha_n = 0 \).

While the size scaling \( \alpha_R \) is not experimentally determinable from the C-Mod data, imposition of the "Kadomtsev constraint", the assumption that the (non-dimensionalized) confinent time can be represented as a function of non-dimensional physics parameters excluding the Debye scale, can be used to infer a self-consistent size scaling from the experimental data. The relevant expressions are presented, for example, in the review paper by Luce [1]. Specifically, the confinement time is re-cast (see Table 5 of [1]) as

\[
\Omega_i \tau_E \propto \rho^{\alpha_\rho} \beta^{\alpha_\beta} \nu_C^{\alpha_\nu} q^{\alpha_q} (R^{R,D})
\]

where \( \nu_C = \bar{n}_e R/T_e^2 \) is used as the collisionality measure, the dependence on \( \kappa \) and shape \( \epsilon \) has been suppressed as in 1 due to the lack of variation in the experimental data, and we will assume no intrinsic size scaling \( \alpha_{R,D} = 0 \). In this case, the non-dimensional exponents in terms of the dimensional ones are [1]:

\[
\alpha_\rho = \left[ -\frac{3}{2} \alpha_I + \frac{3}{2} \alpha_B - 3 \alpha_P - 2 \alpha_n \right]/(1 + \alpha_P) - \frac{3}{2}
\]

\[
\alpha_\beta = \left[ -\frac{1}{4} \alpha_I + \frac{1}{4} \alpha_B + \frac{3}{2} \alpha_P + \alpha_n \right]/(1 + \alpha_P) + \frac{1}{4}
\]

\[
\alpha_\nu = \left[ -\frac{1}{4} \alpha_I - \frac{1}{4} \alpha_B - \frac{7}{2} \alpha_P \right]/(1 + \alpha_P) - \frac{1}{4}
\]

\[
\alpha_q = -\alpha_I/(1 + \alpha_P)
\]

which, plugging in the exponents from Eq. (1), gives

\[
\Omega_i \tau_E \propto \rho^{3.4} \beta^{0.206} \nu_C^{0.56} q^{-0.96}
\]
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.

In order to carry out scans of the non-dimensional parameters, the engineering parameters need to be varied simultaneously. The control parameters, typically, $I_p$, $\bar{n}_e$, and $B_T$, are set to prescribed values, and the auxiliary power is varied in order to achieve the required value of $T$ (or $W$, the plasma stored energy). For all of the scans, except for $q$, it is necessary to vary $B_T$. For C-Mod, this is problematic because, even for a single ICRF heating scenario, e.g. D(H) minority heating, the resonance location moves with the field, so some variation in the effectiveness of the heating is to be expected. For significant changes in field, the heating scenario has to change, raising issues of significant variation in the single-pass absorption and overall heating efficiency; this is especially a concern in the case of $B_T \approx 8T$ where D(He$^3$) minority or mode conversion heating is required, and single-pass absorption is low and varies with plasma parameters. At least for cases with sufficient H/(H+D), the second harmonic D(H) minority scenario at $B \sim 2.7T$ has high absorption. However, based on the results of MP#$735$, the range of density and power accessible in I-mode at 2.7T is very narrow, so the best we could do is use this condition as a low field anchor and vary $n_B$ and $q$ at companion high field cases at $B \sim 5.4T$. We aim to carry out as much as possible of the dimensionless parameter scan using the standard D(H) minority heating scheme with $B_T \sim 5T$.

The necessary scalings, with fixed geometry, in order to scan $\rho_*$ at constant $\beta$, $\nu_C$, and $q$, assuming fixed geometry, are (after [1] Table 4):

<table>
<thead>
<tr>
<th>Scan</th>
<th>$I$</th>
<th>$n$</th>
<th>$T(P_{Loss})$</th>
<th>$W(P_{Loss})$</th>
<th>$B$</th>
<th>$\tau$</th>
<th>$P_{Loss}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho_*$</td>
<td>B</td>
<td>$B^{4/3}$</td>
<td>$B^{2/3}$</td>
<td>$B^2$</td>
<td>$\rho_*^{2/3}$</td>
<td>$B_3^{-1} \rho_*^{\alpha_{p}}$</td>
<td>$B_3^3 \rho_*^{\alpha_{p}}$</td>
</tr>
<tr>
<td>$\beta$</td>
<td>B</td>
<td>$B^4$</td>
<td>$B^2$</td>
<td>$B^6$</td>
<td>$\beta^{-4}$</td>
<td>$B_3^{-1} \beta^{\alpha_{p}}$</td>
<td>$B_3^7 \beta^{\alpha_{p}}$</td>
</tr>
<tr>
<td>$\nu_C$</td>
<td>B</td>
<td>$B^4$</td>
<td>$B^2$</td>
<td>$B^2$</td>
<td>$\nu_C^{-4}$</td>
<td>$B_3^{-1} \nu_C^{\alpha_{p}}$</td>
<td>$B_3^3 \nu_C^{\alpha_{p}}$</td>
</tr>
<tr>
<td>$q$</td>
<td>$q^{-1}$</td>
<td>$-$</td>
<td>$-$</td>
<td>$-$</td>
<td>$q^{2\alpha_{p}}$</td>
<td>$B q^{\alpha_{p}}$</td>
<td></td>
</tr>
</tbody>
</table>

In the above table, the $q$-scan is to be carried out at fixed field and density by means of a current scan, while scans of the other parameters are based on variation of $B_2$, varying $\bar{n}_e$ as a function of $B_1$ and adjusting the input power to match the temperature (or stored energy), essentially according to the loss power scaling from column 8.

In practice, we will use the global stored energy $W_{MHD}$ as the matching criterion, rather than the local parameter $T(\bar{\psi}_n)$. Since we are performing constrained scans rather than non-dimensional identity experiments, neither the dimensional nor the non-dimensional profiles are guaranteed to be self-similar. Therefore, we would need to specify which local parameter we wanted to constrain, depending on what we believe to be the important physics. Using the global quantity $W$ is essentially equivalent to interpreting $\nu_C$ and $\rho_*$ as the equivalent functions of the volume-averaged (or density-averaged) temperature. Using $W_{MHD}$ instead of $W_{th}$ is a further experimental convenience, since we need to evaluate the match on the fly during the run, and the necessary kinetic profiles are less readily available in the control room after each shot.

In terms of experimental protocol, we would attempt to set the desired $\bar{n}_e$, $B_T$, $I_p$ for each condition, and program the RF in a staircase waveform with levels implied by the expected range of $\tau_E$, as determined from the table. Each step will need to last several confinement times, so probably 3 steps can be used for each shot, with subsequent shots as needed to refine the match and account for variations of the nominal parameters with power. Note the loss power, including $P_{ohm}$, is required; any $dW/dt$ term should also be accounted for, but quasi-steady conditions should be obtained.

Since the dependence of kinetic profiles on the non-dimensional parameters is an essential aspect of under-
standing and applying the results, we expect to request HIREX-SR profiles for all conditions, unless and until argon puffing causes access problems. The run plan therefore includes a locked mode calibration shot early in the sequence.

In planning the range of non-dimensional parameters to be attempted, the problem is to devise a sufficient range in the scanned parameter to determine the scaling, within constraints of sufficient power to maintain the I-mode, and low enough power and density to avoid an I→H transition. We need to respect the L→I threshold power \[ P_{th}(MW) = 2.11I^{0.94}n_e^{0.65} \] (11)

where \( I \) is in MW and \( n_e \) is in \( 10^{20} m^{-3} \). Based on recent results and consideration of the span of the existing database, we propose to carry out the scans around a recent, mid-performance I-mode at 5.65T, 1.1MA, \( n_e = 1.3 \times 10^{20} m^{-3} \). The corresponding non-dimensional parameters for 1160816007 were \( \rho_\ast = .0091, \beta_T = .91\%, \nu_C = 0.021, q_{95} = 3.56, B\tau_E = 0.23 \). Within a range of fields \( 4.6 < B_T < 6.1 \) and available power \( 2 < P_{loss} < 5MW \) (where the effective lower bound is set by the L→I threshold \[ 11 \] for each case), we propose single parameter scans over \( 0.0087 < \rho_\ast < 0.0105, 0.6 < \beta_T(\%) < 1.1, 0.016 < \nu_C < 0.040, \) and \( 3.1 < q_{95} < 4.2 \). Depending on the time available, we will attempt to obtain intermediate points for each parameter, in addition to the base case, to guard against effects related to location of the ICRF resonance, as well as possible proximity to operational boundaries, e.g. L→I, I→L, I→H thresholds at the extreme points.

The planned scans over \( \beta \) and \( \nu_C \) cover a variation of about a factor of 2 or more, while the variation in \( q_{95} \) covers the range of expected interest for a high performance facility, and is sufficient to distinguish, for example, between the predictions \( \alpha_q \approx -1 \) from the I-mode database and \( \alpha_q \approx -3 \) implied by the IPB H-mode scaling. While the proposed range of \( \rho_\ast \) is small, only 20\%, the expected gyroBohm-like scaling is \( B\tau \propto \rho_\ast^{-3} \) so substantial changes, up to a factor of two, are anticipated in \( B\tau_E \). The proposed scan already covers the full range of field around 5T. If the scaling turns out to be closer to Bohm than gyroBohm, it may be necessary to attempt a point at 2.7T.

4 Resources

4.1 Machine and plasma parameters

Give values or range for all of the following:

| Toroidal field | 4.6 to 6.1T (reverse field) |
| Plasma current | \( 0.85 \leq I_p \leq 1.3 \) MA |
| Working gas species | deuterium |
| Density | \( \bar{n}_e \approx 0.8 - 1.5 \times 10^{20}\ m^{-3} \) |
| Equilibrium configuration | Reference shot 1160816007 |
| Pulse length, typical current and density waveforms, etc. | As in shot 1160816007 |
| Boronization required? | No |

(If yes, specify whether overnight or between-shot, how recently needed, and any special conditions.)
4.2 Auxiliary systems

List requirements for the following Alcator C-Mod auxiliary systems:

- **ICRF** (power, pulse length, phasing) Request up to 5.0 MW, turning on at $t = 0.6$ s
- **LHCD** (power, pulse length, phasing) Not required
- **Pellet injection** (list species) N/A
- **Impurity injection** (laser blow-off) No
- **Diagnostic neutral beam** Not required.
- **Special gas puffing** Nitrogen ($N_2$) or Neon puffing for seeding. May need $H_2$ available if we end up needing points at 2.7T.
- **Cryopump** Yes
- **Non-axisymmetric coils** Standard for locked mode suppression (reverse field)

Other

4.3 Diagnostics

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

- **Essential:**
  - magnetics
  - TCI
  - GPC and/or GPC2
  - neutrons
  - Thomson scattering for $T_e$ and $n_e$ profiles, including pedestal
- **Useful:**
  - Reflectometer, polarimeter for WC mode
  - PCI
  - HIREXSR for $T_i$, rotation documentation

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 run day is required, with the possibility of extension to 9 hours. A minimum of 9 distinct data points (sets of $\rho \alpha_\star$, $\beta$, $\nu_c$, and $q_{95}$ are proposed, with intermediate or alternate points added as dictated by the results.
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.

The scans in the following proposed steps are based on variations about the proposed reference discharge. The specific bounds in the various scans need to be checked for feasibility based on the results from recent experiments, especially the scans carried out during the week of August 22, 2016 under MP#822. The predicted $\tau_E$ and $P_{\text{loss}}$, based on the Walk regression and the H-mode scaling $\tau_{E,98}^{H,98}(y^2)$ are shown for guidance. Both scalings are close to gyroBohm scaling ($\rho_*^{-3}$); if the actual I-mode scaling turns out to be weaker, closer to Bohm-like $\rho_*^{-2}$, then it might be necessary to include a point at 2.7T in order to pin down the scaling. The range of accessible $q_{95}, \nu_C$ and $\beta$ with $B_T \sim 5.4 \pm 0.8$ is expected to be sufficient to provide some meaningful constraints on those scalings.

The order of the scans in steps 3-6 may need to be reconsidered, depending on results and time allocation. The suggested ordering is intended to minimize the number of large inter-shot field and current changes, while completing each scan in one block of shots before moving on to the next. This may not be the most efficient approach.

1. Establish reference shot, tweak strike points, gaps as needed [1-3 shots]

2. Locked mode calibration shot [1-2 shots]
   Example: Shot#1160825008, segment 4.

3. $q_{95}$ scan at reference field $B=5.65T$. This is essentially a current scan, keeping $\bar{n}_e$ constant, and adjusting the power to get back to reference $W_{MHD} \approx 150kJ$, and therefore $\beta, \nu_C$, and $\rho_*$, at each current. (The first line in each of the following tables represents the reference values, as reproduced in Step#1.) [5 shots]

<table>
<thead>
<tr>
<th>$q_{95}$</th>
<th>$B_T$</th>
<th>$I_p$(MA)</th>
<th>$\bar{n}_e(10^{20}m^{-3})$</th>
<th>$T_{e0}(keV)$</th>
<th>$W$ (kJ)</th>
<th>$\tau_{E,I}^{(w3)}$</th>
<th>$P_{I,\text{loss}}^{(w3)}$</th>
<th>$\tau_{E,98}^{H,98}(y^2)$</th>
<th>$P_{E,\text{loss}}^{H,98}(y^2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.56</td>
<td>5.65</td>
<td>1.1</td>
<td>1.24</td>
<td>6.2</td>
<td>151</td>
<td>.040</td>
<td>3.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.1</td>
<td>5.65</td>
<td>1.26</td>
<td>1.24</td>
<td>6.2</td>
<td>151</td>
<td>.046</td>
<td>3.3</td>
<td>.060</td>
<td>2.5</td>
</tr>
<tr>
<td>3.8</td>
<td>5.65</td>
<td>1.03</td>
<td>1.24</td>
<td>6.2</td>
<td>151</td>
<td>.038</td>
<td>4.0</td>
<td>.033</td>
<td>4.6</td>
</tr>
<tr>
<td>4.2</td>
<td>5.65</td>
<td>0.93</td>
<td>1.24</td>
<td>6.2</td>
<td>151</td>
<td>.034</td>
<td>4.4</td>
<td>.024</td>
<td>6.2</td>
</tr>
</tbody>
</table>

4. $\rho_*$ scan. The predicted variation in confinement over the nominal range for $\alpha_\rho \approx -3$ is small but should be visible. If the scaling is weaker than expected, then it may be necessary to either attempt a higher field point, $B_T \sim 6.2$ or to touch base with the low-field ($B_T \approx 2.7T$) point. The last two lines in the table below show the contrast between the (slightly better than) gyro-Bohm scaling I(w3) and a pure Bohm scaling $\alpha_\rho = -2$. The low-field 2.7T point clearly distinguishes these cases (factor 2 in $\tau_E$ and loss power). If we decide to take data at 2.7T, we would need to use H$_2$ puffing to increase the minority fraction and prevent fast ion induced melting to the limiter with the 2$\Omega_eH$ scenario. [4-8 shots]:

<table>
<thead>
<tr>
<th>$\rho_*(10^{-3})$</th>
<th>$B_T$</th>
<th>$I_p$(MA)</th>
<th>$\bar{n}_e(10^{20}m^{-3})$</th>
<th>$T_{e0}(keV)$</th>
<th>$W$ (kJ)</th>
<th>$\tau_{E,I}^{(w3)}$</th>
<th>$P_{I,\text{loss}}^{(w3)}$</th>
<th>$\tau_{E,98}^{H,98}(y^2)$</th>
<th>$P_{E,\text{loss}}^{H,98}(y^2)$</th>
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</thead>
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<tr>
<td>9.1</td>
<td>5.65</td>
<td>1.1</td>
<td>1.24</td>
<td>6.2</td>
<td>151</td>
<td>.040</td>
<td>3.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.5</td>
<td>4.59</td>
<td>0.89</td>
<td>0.94</td>
<td>5.4</td>
<td>99.5</td>
<td>.031</td>
<td>3.3</td>
<td>.034</td>
<td>2.95</td>
</tr>
<tr>
<td>8.7</td>
<td>6.08</td>
<td>1.18</td>
<td>1.37</td>
<td>6.5</td>
<td>175</td>
<td>.044</td>
<td>4.0</td>
<td>.042</td>
<td>4.15</td>
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<table>
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<tr>
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<th>*</th>
<th>*</th>
<th>*</th>
<th>*</th>
<th>*</th>
<th>$\tau_{E,\text{Bohm}}$</th>
<th>$P_{E,\text{loss}}^{\text{Bohm}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.3</td>
<td>6.53</td>
<td>1.27</td>
<td>1.50</td>
<td>6.8</td>
<td>201</td>
<td>.048</td>
<td>4.2</td>
<td>.043</td>
<td>4.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14.9</td>
<td>2.70</td>
<td>0.53</td>
<td>0.46</td>
<td>3.8</td>
<td>34</td>
<td>.016</td>
<td>2.2</td>
<td>.031</td>
<td>1.1</td>
<td></td>
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5. $\nu_C$ scan [5 shots]

<table>
<thead>
<tr>
<th>$\nu_C$</th>
<th>$B_T$</th>
<th>$I_p$(MA)</th>
<th>$\bar{n}_e(10^{20}m^{-3})$</th>
<th>$T_{e0}(keV)$</th>
<th>W (kJ)</th>
<th>$\tau_E^{I(w3)}$</th>
<th>$P_{Loss}^{I(w3)}$</th>
<th>$\tau_E^{H98(y2)}$</th>
<th>$P_{Loss}^{H98(y2)}$</th>
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<tbody>
<tr>
<td>.021</td>
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<td>1.24</td>
<td>6.2</td>
<td>151</td>
<td>.040</td>
<td>3.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>.016</td>
<td>6.02</td>
<td>1.17</td>
<td>1.24</td>
<td>7.0</td>
<td>171</td>
<td>.043</td>
<td>4.0</td>
<td>.037</td>
<td>4.7</td>
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<tr>
<td>.040</td>
<td>4.79</td>
<td>0.93</td>
<td>1.24</td>
<td>4.5</td>
<td>108</td>
<td>.033</td>
<td>3.35</td>
<td>.050</td>
<td>2.2</td>
</tr>
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6. $\beta$ scan [5 shots] (values in red are not feasible, $\tau_E^{H98}$ scaling would require less ambitious range of $\beta$)

<table>
<thead>
<tr>
<th>$\beta$(%)</th>
<th>$B_T$</th>
<th>$I_p$(MA)</th>
<th>$\bar{n}_e(10^{20}m^{-3})$</th>
<th>$T_{e0}(keV)$</th>
<th>W (kJ)</th>
<th>$\tau_E^{I(w3)}$</th>
<th>$P_{Loss}^{I(w3)}$</th>
<th>$\tau_E^{H98(y2)}$</th>
<th>$P_{Loss}^{H98(y2)}$</th>
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<tbody>
<tr>
<td>.91</td>
<td>5.65</td>
<td>1.1</td>
<td>1.24</td>
<td>6.2</td>
<td>151</td>
<td>.040</td>
<td>3.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>.6</td>
<td>5.09</td>
<td>1.0</td>
<td>0.8</td>
<td>5.0</td>
<td>81</td>
<td>.041</td>
<td>2.0</td>
<td>.065</td>
<td>1.2</td>
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<td>1.1</td>
<td>5.92</td>
<td>1.15</td>
<td>1.5</td>
<td>6.8</td>
<td>200</td>
<td>.040</td>
<td>5.1</td>
<td>.032</td>
<td>6.3</td>
</tr>
</tbody>
</table>

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.

Successful completion of a dimensionlessly-constrained scaling will facilitate projections of I-mode performance to present and future devices. In addition, it may provide some physical insight into the I-mode transport regime, as well as data suitable for model validation studies.

References

