Alcator C-Mod

Mini-Proposal

MP No. 779

Subject: High-Field ELMy H-Modes at the Extreme of EPED Prediction

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Group: Pedestal

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Approved by: Date approved:

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 “sales pitch” for your use of a C-Mod run day.

The goal of this experiment is to develop a body of well-characterized and well-diagnosed data from discharges running ELMy H-modes at 8 T for subsequent modeling efforts. First, the experiments will provide a substantial body of data at high field to expand upon previous tests at Alcator C-Mod of the EPED model for the H-mode pedestal – these data represent the extreme of the range of parameters used in EPED prediction. Second, this experiment will produce a range of data spanning a range of strong diamagnetic stabilization of pedestal instabilities, providing input for a detailed study of the upper range of diamagnetic stabilization for the EPED-associated instabilities using BOUT++, again improving the characterization of instabilities used in the EPED model at high densities and magnetic fields. Third, the data generated here will be useful for modeling studies concerning the effects of very low $\rho^*$ and strong $E \times B$ shearing on pedestal turbulence and structure.

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).

Due to its good performance, capacity for stationary operation with limited impurity accumulation, and ready accessibility on a variety of devices, the ELMy H-mode is considered the baseline for high-performance operation on ITER [1]. However, on ITER- and reactor-scale devices ELMs drive transient heat loads leading to untenable erosion and damage to plasma-facing materials [2]. As such, a predictive understanding of the stability limits associated with the ELM trigger is essential for planning operating scenarios avoiding, mitigating, or suppressing large, deleterious ELMs.

The EPED model [3] combines constraints from peeling-ballooning MHD stability calculated in ELITE [4] and from the onset of kinetic-ballooning mode (KBM) turbulence [5]. Using a set of simple, scalar engineering inputs, EPED uniquely predicts the pedestal width and height at the ELM stability limit. EPED predictions have been implemented for ELMy H-modes on a number of devices [6], including on
Figure 1 – Pressure pedestal heights in ELMy H-mode on C-Mod & DIII-D versus EPED predictions for the same. Also shown is the ITER projection from EPED.

Alcator C-Mod [7] – data from which represents the peak magnetic field, density, and thermal pressure in H-mode tested in the model, within a factor of ∼ 2 of the ITER target pedestal (Fig. 1).

The calculation of peeling-ballooning MHD instability in EPED requires an accounting of the effect of diamagnetic stabilization in the pedestal. For rapid calculation of the pedestal prediction, EPED uses a simple analytic model for the diamagnetic stabilization – in earlier versions of the code (EPED1) the diamagnetic term was taken to be fixed at the half-maximum for the analytic pedestal structure used in the code [8], while later versions of the code (currently EPED1.6) use a fit to prior calculations of the diamagnetic term using the BOUT++ fluid code, resulting in a bi-linear model with stronger stabilization for higher toroidal mode numbers [9].

However, there are several key aspects to the model that have not been sufficiently covered in prior experiment. First, while prior EPED experiments on Alcator C-Mod included data at the maximum toroidal field of 8T, coverage in the dataset at this parameter range was limited due to operational difficulties (namely, the necessity to shift to 3He minority ICRF heating coupled with the high H-mode threshold power inherent to high-field operation). As such, an expanded dataset at maximum field will allow a more thorough validation of EPED at the extreme of its parameter range. Moreover, the effect of diamagnetic stabilization in the comparatively high-collisionality H-mode pedestal on C-Mod is quite strong; previous EPED experiments already required an ad-hoc modification (EPED1.63) to the stabilization model to better account for the effect. A more direct characterization of the diamagnetic stabilization effect in the pedestal using BOUT++ will be instrumental in expanding and refining the applicable range of the EPED model. This examination will also provide data at very low $\rho^*$ and with strong $E \times B$ shearing rates, testing theoretical suggestions of modified effects potentially accessed at high field (see Fig. 2 for range in C-Mod H-modes).

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,
The approach here is relatively straightforward, as the aim is to fill in a dataset over a relatively limited range. All plasmas will be run at 8 T, in the “JFT-2M” shape, which has been shown to optimize access to ELMy H-mode on C-Mod [9] (see Fig. 3) – for reference, see equilibrium in shot 110107030. Operation will be similar to the high-field range of the field scan in MP636 – the notable differences being (a) operation at a somewhat lower density (and thus higher $P_{\text{loss}}/P_{\text{thres}}$), and (b) the inclusion of GPI and CXRS data for detailed turbulence spectra and $E \times B$ shearing rates in the edge for later comparison to modeling efforts.

The primary parameter scans will be in density, plasma current and heating power, to vary the pedestal collisionality and diamagnetic frequency. The plasma current range, however, is rather small, as it is bounded to $\sim 750$ kA at the lower end by edge safety-factor limits, and to $\sim 1000$ kA by power-supply limits on the equilibrium magnetic coils. Shots will therefore scan plasma current within this range. Plasma density will run somewhat lower than typical for these experiments, to reduce the H-mode threshold power and boost edge temperature at the given pedestal $\beta_p$ limit. The density range will consist of a low- and a high-$n_e$ target, with L-mode line density targets at $n_{\text{L04}} = 0.4 \times 10^{19}$ m$^{-2}$ – density control is rather inconsistent in these H-modes, so the L-mode target is the more meaningful “knob.” However, this should result in H-mode average densities of $\pi_e \sim 1.1 \times 10^{20}$ m$^{-3}$. At each current/density point, the ICRF power is scanned at 3, 4, and 5 MW – At the highest point ($B_T \sim 8$ T, $\pi_e \sim 2.2 \times 10^{20}$ m$^{-3}$ in JFT-2M shape, per reference shot 1110107030) the H-mode threshold power is roughly 2.5 MW, this (with Ohmic power) should be sufficient to generate H-modes while driving variation in the temperature pedestal at fixed current and target density.

This will generate a healthy number of high-field H-modes for EPED validation (supplementing the substantial dataset at standard field already used), as well as providing a range of cases for BOUT++ modeling despite the relatively restricted parameter range. Each current/density/power point will puff simultaneously for CXRS and GPI, generating a body of edge $E \times B$ shear profiles and turbulence spectra for later comparison to simulation. Additionally, magnetic measurements using the dual-coil head of the A-port

Figure 2 – Pedestal width normalized to the EPED1 prediction versus $\rho_{95}^{\ast}$. This experiment will target the lower range ($\rho^{\ast} < 0.003$) at high field.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{Pedestal width normalized to the EPED1 prediction versus $\rho_{95}^{\ast}$. This experiment will target the lower range ($\rho^{\ast} < 0.003$) at high field.}
\end{figure}
Figure 3 – C-Mod cross-section showing both the typical plasma shape, and the modified “JFT-2M” shape favorable to ELMy H-mode access.
scanning probe will connect with prior measurements of the inter-ELM fluctuation [10] and extend these measurements to high field.

4 Resources

4.1 Machine and plasma parameters

Give values or range for all of the following:

<table>
<thead>
<tr>
<th>Toroidal field</th>
<th>8.0 T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma current</td>
<td>0.7 – 1.0 MA</td>
</tr>
<tr>
<td>Working gas species</td>
<td>Deuterium (D$_2$)</td>
</tr>
<tr>
<td>Density</td>
<td>$n_{i04} \approx 0.4 – 0.8 \times 10^{19}$ m$^{-2}$ (L-mode target)</td>
</tr>
<tr>
<td>Equilibrium configuration</td>
<td>Reference shot 1110107030</td>
</tr>
<tr>
<td>Pulse length, typical current and density waveforms, etc.</td>
<td>As in shot 1110107030. Aim for ELMy H-mode regime.</td>
</tr>
<tr>
<td>Boronization required?</td>
<td>Yes, prior overnight boronization necessary.</td>
</tr>
</tbody>
</table>

4.2 Auxiliary systems

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

<table>
<thead>
<tr>
<th>ICRF (power, pulse length, phasing)</th>
<th>Request 5.0 MW, turning on at $t = 0.5$ s, ramp to full power at $t = 0.75$ s until rampdown</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHCD (power, pulse length, phasing)</td>
<td>Not required</td>
</tr>
<tr>
<td>Pellet injection (list species)</td>
<td>N/A</td>
</tr>
<tr>
<td>Impurity injection (laser blow-off)</td>
<td>Not required. May piggyback.</td>
</tr>
<tr>
<td>Diagnostic neutral beam</td>
<td>Not required.</td>
</tr>
<tr>
<td>Special gas puffing</td>
<td>Nitrogen (N$_2$) puffing through NINJA system for impurity seeding. Argon (Ar) available for HiReX SR. Deuterium (D$_2$) puffing for CXRS. Deuterium puffing for GPI.</td>
</tr>
<tr>
<td>Cryopump</td>
<td>Required for density control during boronization recovery</td>
</tr>
<tr>
<td>Non-axisymmetric coils (list connections and current)</td>
<td>Not required</td>
</tr>
<tr>
<td>Other</td>
<td>None</td>
</tr>
</tbody>
</table>
4.3 Diagnostics

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

- Core and edge Thomson Scattering: edge fibers arranged for JFT-2M shape
- CXRS $T_i$, $E_r$ profiles / $E \times B$ shearing rate
- GPI turbulence spectra
- HiReX SR $T_i$ (incl. Ar puffing)
- dual-coil magnetics head on A-port Scanning Probe (ASP)
- ECE $T_e$, arranged for high field operation
- PCI for $^3$He fraction/mode conversion measurement
- O-mode reflectometer for edge $\tilde{n}_e$

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.

Given sufficient RF preparation for high field has been completed, a single extended run day following a recent overnight boronization is sufficient. If necessary, the initial phase of the day will focus on RF preparation. For the planned shot sequence, one standard run day will be sufficient.

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.

Phase I: boronization recovery

Some recovery / outgassing will be necessary from the overnight boronization immediately preceding the run. Allow shots at 5.4 T (for more rapid recool turnaround time) in JFT-2M shape, until low-density 5.4 T ELMy H-mode is achieved. Allow up to 10 shots.

total: 5-10 shots

Phase II: high-field phase

This will be the main phase of the experiment, consisting of the current, RF power, and density scans. All shots will be in the JFT-2M shape (see reference shot 1110107030) at 8.0 T. The shot sequence will progress through the current range at $I_p = 0.75, 0.9, 1.0$ MA. At each current point, there will be a low- and a high-density target, targeting L-mode line densities $n_{l04}$ of $0.4, 0.8 \times 10^{19} \text{m}^{-2}$. For each, the RF power will scan at 3, 4, 5 MW to adjust the temperature pedestal. GPI and CXRS will puff simultaneously, obtaining both the CXRS $E_r$ well and the GPI turbulence spectra.

total: 18 shots
This allows for 23-28 shots including boronization recovery, ICRF tuning, and preparation, which should be achievable in a single extended run day. If phase I is achieved ahead of schedule these shots will allow for a buffer for any run issues.

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.

This experiment will provide a healthy high-field dataset with well-characterized pedestal profiles (electron and ion profiles, $E_r$ well, $E \times B$ shear, turbulence spectra) for later modeling use. Immediately, these data can be used for further validation of the EPED model on C-Mod, extending the already substantial dataset at higher fields and densities at which the model has been tested. The data will be analyzed in BOUT++ to more directly examine the strong diamagnetic-stabilization effects unique to C-Mod, potentially modifying the simplifying assumptions used in EPED for the peeling-ballooning stability calculations. Furthermore, the data provided by the experiment will potentially shed light on turbulence effects at low $\rho^*$ and high $E \times B$ shearing rates, potentially modifying the limiting assumptions for ELMy H-mode pedestal. Inter-ELM pedestal fluctuations from the ASP will connect with previous experiments at standard field, and extend these to high field.
References


