Subject: Species effects on the H-mode threshold in He4(H), D(H), and H(He3) plasmas

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Group: H-mode Scenarios

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1. Purpose of Experiments
Include immediate goal of the experiments, scientific importance and/or programmatic relevance. Refer to any relevant program milestones.

The ITER Research Plan [1] intends to begin operation in He4 and H plasmas to bring the machine up to full technical performance \( (I_p = 15 \text{ MA}, B_T = 5.3 \text{ T}) \) before the machine becomes activated in the D and DT phases. It would be very beneficial to the ITER program if H-mode operation can also be demonstrated in these early operational phases to enable early assessment of a variety of issues that would otherwise not be addressed until the D or DT phases. However, it is unclear whether ITER will have sufficient auxiliary power to achieve H-mode during this phase, even at half-field, and even if this is possible the extrapolation of the results to the D and DT phase of ITER operation will need to be based on experimental determination of the isotopic dependence of H-mode characteristics in current devices. The purpose of this experiment is to compare the H-mode threshold, pedestal characteristics, and confinement properties in majority helium and hydrogen plasmas with those obtained in deuterium plasmas. Comparison of type-I ELMy H-mode characteristics in helium and deuterium plasmas will be the subject of a separate Mini-proposal. An improved understanding of the H-mode threshold power required to achieve H-mode in H and He plasmas would help to reassure or modify the ITER Research Plan.

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

The H-mode threshold in H plasmas is well-established to be about twice as high as in D plasmas [2,3,4,5]. On the other hand, the L-H power threshold in helium is less well-known. Experiments on JET [6] indicated that the helium threshold was about 40% higher than in D, while recent results from ASDEX-Up grade indicate that the H-mode threshold is nearly the same in He4 as it is in D plasmas [7,8]. Both of these experimental results suggest that helium operation in ITER may be favorable to early access to H-mode during the pre-activation phase. However, the quantitative discrepancy makes the projection to ITER uncertain, and potentially reduces the value of proposed ITER experiments for assessing the adequacy of the ITER heating and current drive system. It
would be valuable to compare these H-mode threshold results with C-Mod results at ITER relevant density and toroidal field. Furthermore, the L-H threshold in hydrogen has not been studied in C-Mod, and a comparison of the relative threshold in H and D in C-Mod, also at the ITER relevant toroidal field and density and using ITER’s proposed ICRF heating scenario would also be of value.

While the power threshold to achieve H-mode is important in itself, these experiments should also assess the characteristics of the ensuing H-mode. Experience to date with helium H-modes on C-Mod is rather limited. Those that have been produced have tended to be ELM-free, highly radiative, and transient. No steady-state EDA H-mode conditions have been demonstrated in pure helium discharges, although such conditions have been observed with mixed (D and He) majority species. These experiments will allow a direct comparison of the pedestal and core confinement characteristics between identically prepared helium and deuterium discharges.

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.

To determine the effect of main plasma species on the H-mode threshold, experiments will first be performed with H minority ICRF heating in He\(^4\) plasmas (f=80MHz, B=5.4T), and then repeated with similar deuterium majority plasmas on the same day, to minimize the possible effects of wall conditions or other extraneous influences on the comparison. The evolution of the threshold and discharge characteristics will also be monitored during the species changeover, which may require up to ten shots. From the ICRF point of view, the He\(^4\)(H) and D(H) systems are identical, so the heating should be species-independent, facilitating the threshold comparison.

These experiments will be carried out using standard lower single null equilibria, permitting comparison with previously obtained C-Mod results in deuterium as well as with the ITPA threshold database and the recent JET and ASDEX-U helium experiments. We will perform density scans at low-to-moderate density, covering the range of minimum threshold power and extending down to the “low-density limit” in each species. At each density the approximate threshold power will be identified by use of a power ramp, and then the value refined by a series of flat and/or staircase power waveforms for at least three density values. The final step of this waveform should be at least 30% above the threshold value and be sustained long enough to document the evolution of the H-mode either to steady-state or collapse.

A second day of experiments at reduced field (3.3 or 2.7T) is also proposed to determine the B\(_T\) scaling in helium and to further assess the potential for H-mode access in ITER at reduced field during the pre-nuclear phase. The preferred heating scenario for these reduced field threshold experiments would be H minority using f=50MHz (J-port antenna only), retaining the same heating scenario as used at 5.4T; this is also the scenario that would likely be employed for reduced field operation in He majority on ITER. However, 50MHz may not be available on C-Mod in 2009. Alternatively, 2\(^{nd}\) harmonic H minority
at 80MHz and B=2.7 T could be employed. While the single pass absorption is likely to be fairly low, we have successfully applied this scenario in the past, e.g. 1050726036. It will be necessary to calibrate the absorbed power using modulation of the rf and the break-in-slope of the stored energy in order to evaluate the threshold power.

A third set of experiments is proposed with He3 minority heating in H plasmas, to be carried out at the end of the campaign before a scheduled opening of the vessel to avoid difficulties returning to H minority heating. In this case the heating scenario would need to be changed to employ He$^3$ minority in H majority, which would be the likely ITER ICRF scenario. These experiments would also therefore require that FMIT#3 and 4 (J-port antenna) be tuned to 50 MHz. The comparison with the D majority could use D(He$^3$) at 50MHz, but care will be required in assessing the absorbed power and effects of low-single pass absorption because the light and heavy minority (relative to majority) scenarios are not equivalent. Exploration and optimization of the H(He$^3$) scenario on C-Mod should be undertaken in a separate experiment prior to this run day.

4. Resources
4.1 Machine and Plasma Parameters

Give values or range for:

| Toroidal Field: | 5.4 T (day1), 2.7 or 3.3T (day 2) |
| Plasma Current: | 1 MA (day1,3), .5 or .6MA (day2) |
| Working Gas Species: | He$^4$,D$^2$ (Day 1-2); H (day 3) |
| Density: | $4 \times 10^{19}$ m$^{-3}$ – $1.5 \times 10^{20}$ m$^{-3}$ |
| Equilibrium configuration (if possible, refer to database equilibria): LSN like 1090701028 |

4.2 Auxiliary Systems

| RF Power, pulse length, phasing: | Day1: ICRF at 80 MHz up to at least 3 MW |
| | Day2: 50MHz if available, else 80MHz |
| | Day 3: 50MHz |

Pellet Injection (species): None
Impurity blow-off injection: None
Diagnostic Neutral Beam: Not required
Special gas puffing: Ar (small puff) for HIREX, He$^3$(day3)
Non-axisymmetric Coils (Connections, Current): Standard configuration
Other: May use the cryopump for density control
Overnight ECDC in helium

4.3 Diagnostics

List required diagnostics, and any special setup or configuration, e.g. non-standard digitization rate.
Core and edge Thomson for temperature and density profiles.(essential)
HIREX for ion temperature and rotation profiles.(highly desirable)
Bolometry for radiation profile measurements. (essential)
Visible Bremsstrahlung for $Z_{\text{eff}}$ measurements. (essential)
TCI for line density (essential)
Fast scanning probes for SOL flow measurements. (acceptable, not essential)
Fast magnetic pick-up coils, PCI, and Reflectometry for fluctuation measurements. (whatever’s available)
Neutrons for Ti, deuterium fraction
Dalpha
CXRS (edge system): for edge rotation; passive B measurements can contribute, will consider active (i.e., with DNB) if available and shown non-perturbative.

ECE for edge $T_e$, pedestal formation

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.

Three run days are requested, one at 5.4T and one at either 2.7 or 3.3T to compare D and He, and one at 5.4T to compare H and D majority. Each run should have the option to be extended to ten hours if required to accomplish the gas changeover and complete the D part of the experiment. The runs are listed in order of priority, with the expectation that the hydrogen run day may not be feasible during the FY2009 campaign.

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.

Day 1: Density scans in He and D at $I_p=1$MA, $B=5.4$T

Prepare by overnight ECDC in helium. Clean, well-conditioned walls are important, but a fresh boronization is probably not necessary, and may be counterproductive since it would tend to degrade over a long operating day and we need to compare shots from morning to evening. Between-shot ecdc may be required in the afternoon, if wall conditions degrade.

Begin in He. Preferably a helium startup (He in the pre-puff as well as the main fuel plenum) will be developed prior to the run day, to minimize D contamination in the He part of the experiment. If this development has not been done, we may devote no more than five shots to this task; if this is unsatisfactory, refill Btop with 6psi D$_2$ and use a normal startup.

0. Establish “pure” He discharge with ICRH. Observe Dalpha and neutron rate, as well as density rise during RF heating in L-mode to assess outgassing of deuterium from antennas. [2-4 shots]

1. set density $n_{l04}=4e19/m^2$ (nebar~7e19/m$^3$), which is near the low-density limit in D. Program slow RF power ramp (.75MW to 3MW) If H-mode is obtained, document threshold, confinement and pedestal using staircase power waveform. Otherwise, raise density until an L-H transition is obtained and document [3-5 shots]

2. If H-mode was obtained at 4e19 then decrease density to explore low density limit and document. Otherwise, continue increasing $n_{l04}$ in increments of 1 to 2e19/m$^2$ up to a maximum of 9e19 (nebar~1.5e20/m$^3$). Adjust power ramp depending on the threshold range. Document using staircase at least one intermediate density and the high end density. [6-10 shots]
3. Changeover to D plasmas (purge and refill B-top and B-main plenums) using high density target, power ramps. Observe change in threshold (if any) and in H-mode characteristics during changeover. Monitor approach to 100% D using $Z_{\text{eff}}$, neutron rate. If changeover is too slow, consider D$_2$ ecdr between shots. [3-10 shots]

4. Repeat density points from He scan in deuterium. If pressed for time, some intermediate density points can be skipped, and/or staircase/flattop waveform cases restricted. Comparison of threshold behavior near the density minimum is most important. [6-10 shots]

Day 2: Density scans at 3.3 T (or 2.7T) in He and D

Program would be similar to the first day, with wall preparation by He ECDC, beginning the day in helium and proceeding to D in the afternoon. The low-field startup developed under MP#556 (1090710) would be employed, preferably using helium for breakdown as developed prior to or during the Day 1 experiment.

The density scans should cover at least the low density end of the range, including the range covered in the MP#529 experiment on 1080430, and at least high enough to see the positive slope of $P_{\text{thr}}$ vs $n_e$. If 50MHz is not available and we need to use second harmonic minority then additional shots may need to be devoted to determining the absorbed power based on rf modulation and break-in-slope during the L-mode phase.

0. Establish “pure” He discharge with ICRH. Observe Dalpha and neutron rate, as well as density rise during RF heating in L-mode to assess outgassing of deuterium from antennas. [2-4 shots]

1. Scan density in He, low to moderate being sure to identify the low density limit below which we have insufficient power to get a transition. [up to 10 shots]

2. Change over from helium to deuterium, monitoring threshold and confinement and pedestal as we go. [3-10 shots]

3. Repeat density points from He scan in deuterium, and identify low density limit in D if not the same as in He. Compare results with 1080430 (limit nebar~8e19/m$^3$) [up to 10 shots]

Day 3: Density scans in H(He$^3$) and D(He$^3$) at 5.4T, f=50MHz

If a run dedicated to validating the heavy minority H(He$^3$) scenario is scheduled, then that should precede this run.

Prepare the wall by overnight ECDC in Hydrogen (we don’t say that very often!).

The program should essentially follow that of Day 1, substituting H for He, except that the lower power available (3MW max expected at 50MHz) and higher expected threshold in hydrogen will likely restrict the density range at both ends. We also have no idea of
where to expect the low density limit in H plasmas, so the starting density has to be a guess.

1. Start with density identified as being the minimum of the $P_{\text{thr}}$ vs $n$ curve in D and determine threshold power in H (power ranp). If not able to get H-mode up to maximum available power run a shot with modulated rf to verify acceptable power absorption; if necessary, adjust He$^3$ concentration and repeat. If still no H-mode, then try varying density until one is found, and document threshold. [2-8 shots]

2. Complete threshold density scan in H over accessible range, documenting pedestal and confinement characteristics. [10 shots]

3. Changeover to D plasmas, observing change in threshold and plasma behavior. Observe H/D signal to evaluate progress. Evaluate heating efficiency and adjust He$^3$ concentration as indicated. [5-10 shots]

4. Repeat density points from threshold scan in H. Compare results with previous results using D(H) as sanity check. [10 shots or time remaining]

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.

These experiments are critically important to the ITER Research Plan. They will help ITER to determine how the H-mode threshold and ELM behavior change in H and He plasmas for use in the pre-nuclear phases of the ITER program. This experiment also contributes to ITPA Joint Experiment TC-4. The results will be presented at international conferences and published.

7. References

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