Power thresholds and other requirements for H-mode access in ITER scenarios

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ITER was designed based on scaling laws for energy confinement derived from H-mode discharges on existing machines, and thus access to H-mode is essential for ITER to fulfill any part of its experimental mission. Numbers given for the auxiliary power (ICRF, ECH, NBI) available on ITER on Day One tend to be only marginally above the H-mode power threshold as projected from a multi-machine database for deuterium plasmas. Superficially, it would appear that sufficient power exists for H-mode access, but there are concerns nonetheless.

Questions for ITER

First, the initial phase of ITER operation is intended as a low-activation "break-in" period. In this non-nuclear phase, experience will be gained with control systems, disruption avoidance, ELM mitigation etc. Currently this is envisioned as a helium phase, with H-modes. There is currently much less information about power thresholds in He than those in hydrogenic plasmas, which complicates projection to this phase. Because H-mode access and sustainment will be essential to the success of this phase, every critical question that is to be answered for the D-D or D-T phase must also be answered for He. In fact, largely for the purposes of procurement, the answers for this initial phase are needed in a matter of months, and not years.

Second, generally ignored in the development of power threshold scaling laws is the tendency for P_{L-H} on a given machine to grow dramatically as density is lowered below a threshold value. This low-density limit for H-mode access has been documented in an approximate fashion on a number of machines, and has shown some variability. On Alcator C-Mod, the L-mode density below which P_{L-H} begins to exceed twice the scaling law is approximately $8x10^{19}$, which is about *twice* the target L-mode density in the ITER plasma. It is crucial to show that the low-density limit extrapolates favorably to ITER, or substantial increases in the available auxiliary power will be necessary.

There is a question about H-mode quality and achievable confinement when the ratio of input power to threshold power is close to unity, as discussed in a companion paper. A related question is whether marginal power can sustain the H-mode (the so-called L-H-L hysteresis question) in non-traditional H-mode scenarios. One example is the He phase, in which there will be no nuclear heating. Additionally, the ability to trigger and sustain H-mode in the transient current-ramp phases may be desired for the reduction of flux consumption.

High-priority R&D proposed by the ITER Council thus includes the following activities:

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- Determination of power required for H-mode threshold in ITER-like plasma conditions and development of strategies for its minimization.
- Determination of power required for steady Type III H-mode operation in ITER-like plasma conditions and development of strategies for its minimization.
- Determination of power required for steady H_{98} = 1 H-mode (Type I ELMy H-mode, EDA, etc.) in ITER-like plasma conditions and development of strategies for its minimization.
- Determination of power required for H-mode access during plasma current ramp-up/down phases with similar requirements to ITER (normalized dIp/dt, plasma shape evolution, etc.)
- Isotope mass and species scaling (H and He plasmas) of required power for H-mode access, Type III ELMy H-mode, steady H_{98} = 1 H-mode (Type I ELMy H-mode, EDA, etc.) in ITER-like plasma conditions and development of strategies for their minimization.

<u>A workplan to address these questions</u>

Answering these questions poses a distinct challenge, in that the relevant parameters that govern the transition from L- to H-mode are presumably related to the local conditions at the plasma edge, and those quantities have somewhat complex relationships to global variables like average density, field and input power, *i.e.* the sorts of easily measured quantities from which scaling laws are derived. To predict the power threshold in a given configuration on ITER purely from physics considerations, one needs to know 1.) the profiles of the edge plasma in the target discharge, 2.) the local threshold conditions for suppressing the turbulence-driven transport and 3.) the relationship between incremental input power and proximity to the local threshold conditions. Accomplishing these goals is sufficiently challenging on one existing machine; using results from multiple devices to project to ITER is a tall order.

Nonetheless, with some effort, substantial progress could be made in the next 3—5 years. Experimental work would require emphasis on edge diagnostics, particularly those that measure profiles of relevant quantities: density, temperature, and flows for example. Characterization of local fluctuation characteristics leading up to L-H transitions is also important. Other quantities may be of interest as well, such as edge neutral density. Resources must be available to upgrade diagnostic sets as needed, so that spatially and temporally resolved profiles are made available on all devices. Facility upgrades in auxiliary power, and also types of sources, will be needed to extend studies to parameter regimes with very high power thresholds. Whenever possible, ample heating power should be available in multiple forms (NBI, ICRF, ECH *etc.*). Efforts should be made to resolve differences in power threshold results that may arise between different heating schemes, such as NBI *vs.* ICRF H-modes. Modification to H-mode access that are induced by effects such as externally applied torque and fast ions must be accounted for, as a burning plasma device such as ITER does not enjoy such physical features.

Theoretical and simulation support is also essential. In predicting local thresholds, theory must attempt to account for quantities which experiments have suggested play a role, including local values of temperature, density, flows and shears in these quantities. Increased emphasis must be had on edge simulation of turbulence, and the physics mechanisms for suppressing the dominant modes giving rise to transport across the separatrix. A major goal of the theoretical and computational community should in fact be to simulate the trigger mechanisms and dynamics of a L-H transition, and validate results against experimental data. To facilitate comparisons across machines (including non-domestic devices) as well as between experiment and theory, a database containing full profile information should be assembled and be freely accessible to researchers.

Where possible, experiments should be done with a magnetic equilibrium approximating that of ITER, including shape and edge q. The high-priority R&D items for ITER dictate that research should focus on determining a physical basis for extrapolating power thresholds accurately and evaluating P_{in}/P_{th} for ITER, *in both the initial He and eventual nuclear phases*. A component of this research must be the mechanisms responsible for the low-density limit for H-mode access and a determination of whether this limit is important for ITER.