**Multimachine Global Confinement and H-mode Threshold Analysis**

ITPA Confinement and H-mode Threshold Database Working Group\(^*\) presented by J. A. Snipes\(^*\)


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**Introduction**

The ITPA Confinement [1] and H-mode Threshold [2] Database Working Groups analyze global parameters from a number of tokamaks worldwide to better understand the physics of energy confinement in a tokamak and of the transition between L and H-mode. We also aim to improve confinement and threshold predictions for future devices.

**Recent Data**

**Confinement Database**

High density data from
- ASDEX-Upgrade
- DIII-D – from IAEA 2000
- JET

approaching or exceeding the Greenwald density limit allow improved analysis of confinement at high density

**Threshold Database**

New data from
- Alcator C-Mod - inner gap scan + corrections to absorbed PICRF
- ASDEX Upgrade - new divertor DIVIIb, at higher triangularity
- MAST - new initial ohmic double null with low aspect ratio [3,4]
- TCV - at higher safety factor (q95 > 2.5) with a lower threshold
- TUMAN-3M - small circular tokamak with high thresholds

**Confinement Analyses**

The preferred ELMy H-mode confinement scaling found in the ITER Physics Basis document [1] IPB98(y,2) still fits the multi-machine data very well:

\[ \frac{\tau_E}{\tau_{E,\text{IPB98}(y,2)}} = 0.1444 \beta^{0.05} q_0^{1.0} \rho_a^{0.5} \left( \frac{a}{R} \right)^{0.5} \left( \frac{a}{R} \right)^{0.5} \]

The high density data from ASDEX-Upgrade, DIII-D, and JET indicate that, under some conditions with peaked density profiles, it is possible to maintain good global energy confinement (IPB98(y,2) ~ 1) up to and beyond the Greenwald density limit [5] even when the loss power (\( P_L = P_{\text{net}} + P_{\text{abs}} - dW/dt \)) is near the latest H-mode threshold power scaling:

\[ P_{\text{thres}} = 1.67 \eta_e^{0.61} \eta_p^{0.78} \gamma^{0.89} \rho_a^{0.94} \]

Attempts were also made to determine the effects of triangularity and other plasma shaping such as \( q_a / q_i \) on IPB98(y,2) but the database is not well conditioned in these variables to provide consistent results.

**Good energy confinement** (IPB98(y,2) ~ 1) can be obtained in H-mode down to \( P_L / P_{\text{thres}} < 1 \). So, the power necessary to ensure good H-mode confinement is then the H-mode threshold power scaling evaluated at the desired steady-state H-mode density.

**IPB98(y,2) H factor versus n/n_G for ASDEX-Upgrade, DIII-D, and JET** showing that they have small influences on the overall H-factor.
Threshold Analyses

New inner gap scan data from Alcator C-Mod show that the threshold increases sharply only for an inner gap < 3 mm. New triangularity points from ASDEX Upgrade with the DIVIIb divertor suggest that the threshold increases at high triangularity. Higher q<sub>95</sub> > 2.5 data from TCV with lower thresholds have improved its fit to the threshold scalings. TUMAN-3M, a small circular tokamak in Russia, finds very high threshold powers relative to the scalings.

Aspect Ratio Dependence of the Threshold

New low aspect ratio MAST data now extend the range of inverse aspect ratio dependence with all of these devices can be determined. Density below a machine-dependent low density limit with high and low elongation, respectively. MAST has the highest ε, with high and low elongation, respectively. MAST has the highest ε, and has high elongation, yet all three of these devices lie well above the threshold scalings without ε and κ. The initial MAST results are also in a double null configuration where for conventional aspect ratio tokamaks the H-mode threshold is often considerably higher than in single null. Due to the inconsistencies in the data from these machines, no reliable scaling of the threshold power including the inverse aspect ratio dependence with all of these devices can be determined.

Selection Criteria for New Regression Fits

Nine tokamaks satisfy the standard low threshold criteria including deuterium plasmas with a single null with the ion VB drift toward the X-point (excluding PBXM, MAST, and TUMAN-3M). Densities below a machine-dependent low density limit with high thresholds are excluded. The new fits for these 9 tokamaks are (660 points):

\[ P_{\text{thres}} = 1.67 \times 10^{-3} \frac{m^2}{s} \left( B_{\phi} \right) \]  
\[ B_{\phi} = \frac{1}{2} m R \left( 1 + \frac{1}{2} \kappa \right) \]  
\[ a = \frac{a R}{B_{\phi}} \]  
\[ \eta = \frac{4 \pi R a \left( 1 + \frac{1}{2} \kappa \right)}{2} \]

where \( S = 4 \pi a R \left( 1 + \frac{1}{2} \kappa \right) \). The units are MW, \( 10^{12} \) m<sup>2</sup> T<sup>2</sup>, lengths in m. The root mean square error of Eq. 1 is 25% and of Eq. 2 is 26%. The RMSE’s of these fits are about 1% lower than those of the previous work because of the increased scatter in the TCV data. This result has lower density and lower size dependence and higher toroidal field dependence than previously. The other 5 tokamaks are also plotted on the graph below for comparison.

Table: Measured H-mode threshold power vs. regression fits to the data from nine tokamaks (with asterisks) given by Eqs. 1 and 2. The width of the diamonds in the graph includes the standard deviation uncertainty interval of 34 – 80 MW because of the additional TCV data. Similarly, the 1σ error bars are plotted for the JET and PETRAS data. The average measured threshold power, the % RMSE and the % average error are calculated for each data set.

<table>
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<th>Tokamak</th>
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<th>Avg(Eq.1)(MW)</th>
<th>Avg(P/fit)(MW)</th>
<th>%RMSE</th>
<th>%AVGE</th>
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<td>132.20</td>
<td>360.35</td>
</tr>
</tbody>
</table>

Conclusions

Under some conditions with peaked density profiles, it is possible to achieve H factors IPB98(y,2) > 1 and beyond the Grenwald density limit and it is possible to achieve this level of energy confinement at a power level given by the H-mode threshold scaling (Eq. 1) evaluated at the full H-mode density. The latest prediction from 7 tokamaks with ITER similar configurations (Eq. 3) for the threshold power required in deuterium plasmas in ITER at \( n_e = 5 \times 10^{19} \) m<sup>-3</sup> and \( B_T = 5.3 \) T is 44 MW, with a ± 2 standard deviation uncertainty interval of 28 – 71 MW. This is somewhat lower than the previous 6 tokamak scaling [1], which gave a point prediction of 52 MW and a 2-standard deviation uncertainty interval of 34 – 80 MW because of the additional TCV data. Similarly, the predicted thresholds in FIRE (at \( n_e = 2.4 \times 10^{19} \) m<sup>-3</sup>, \( B_T = 7 \) T and ignition at \( n_e = 3.25 \times 10^{19} \) m<sup>-3</sup> , \( B_T = 12 \) T) are 24 MW and 17 MW, respectively. Low \( q_{95} < 3 \) and high \( Z_{eff} > 2 \) also lead to higher threshold power and should be avoided to maintain low thresholds.

References