H-mode Threshold and Confinement Using the International H-mode Database

presented by

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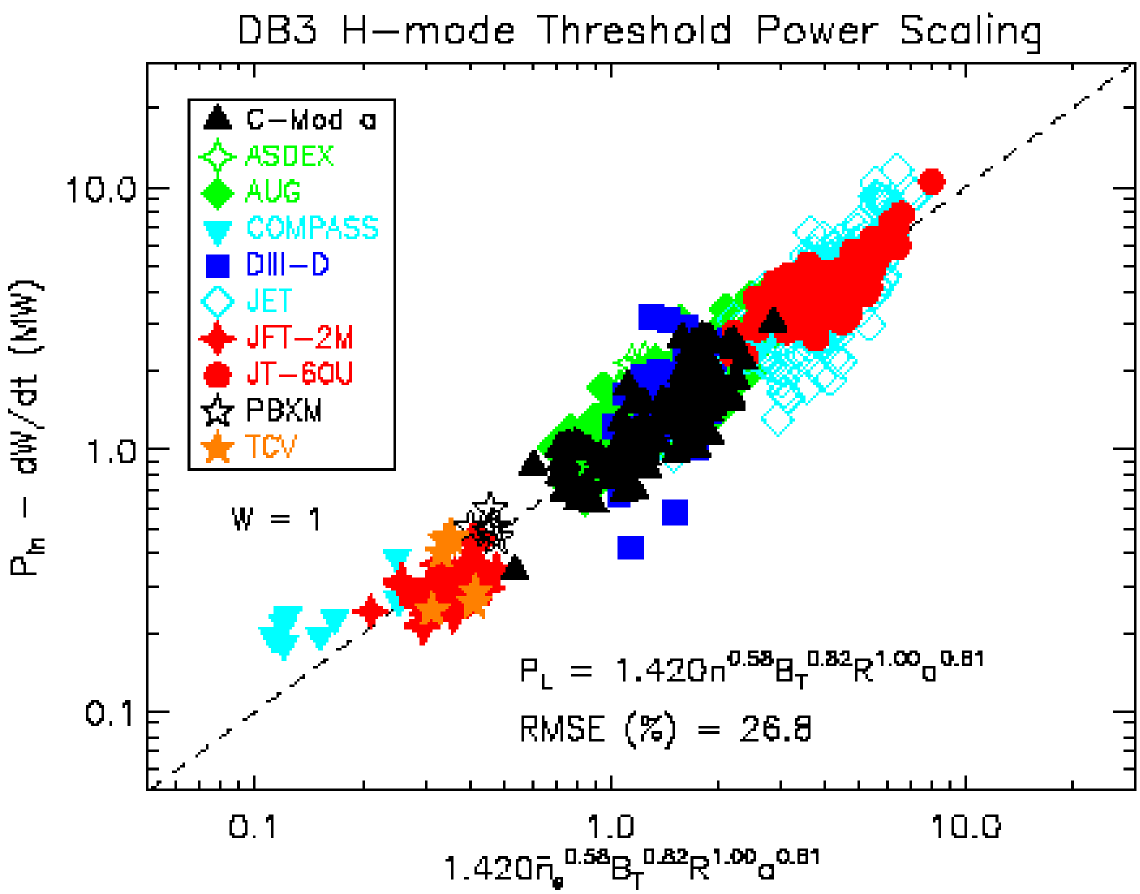
Global Analysis

The global regressions to the H-mode threshold power based on data from 10 different tokamaks are:

$$P_L = 2.84\ M^{-1}\ \bar{n}_e^{0.58}\ B_T^{0.82}\ R^{1.00}\ a^{0.81} \quad \text{RMSE} = 26.8\% \qquad (1)$$

$$P_L = 0.108\ M^{-1}\ \bar{n}_e^{0.49}\ B_T^{0.85}\ S^{0.84} \quad \text{RMSE} = 27.8\% \qquad (2)$$

where $P_L = P_{in} - dW/dt$ is the input power minus the change in the plasma stored energy in MW, M is the atomic mass of hydrogen isotopes, $\bar{n}_e$ is the line averaged density in units of 10^{20} m^{-3}, B_T is the toroidal field on axis in T, R and a are the major and minor radii in m, and S is the plasma surface area in m^2. These regressions gave equal weight to each point. The inverse isotope dependence of the threshold was found by comparing H, D, and T discharges in JET.

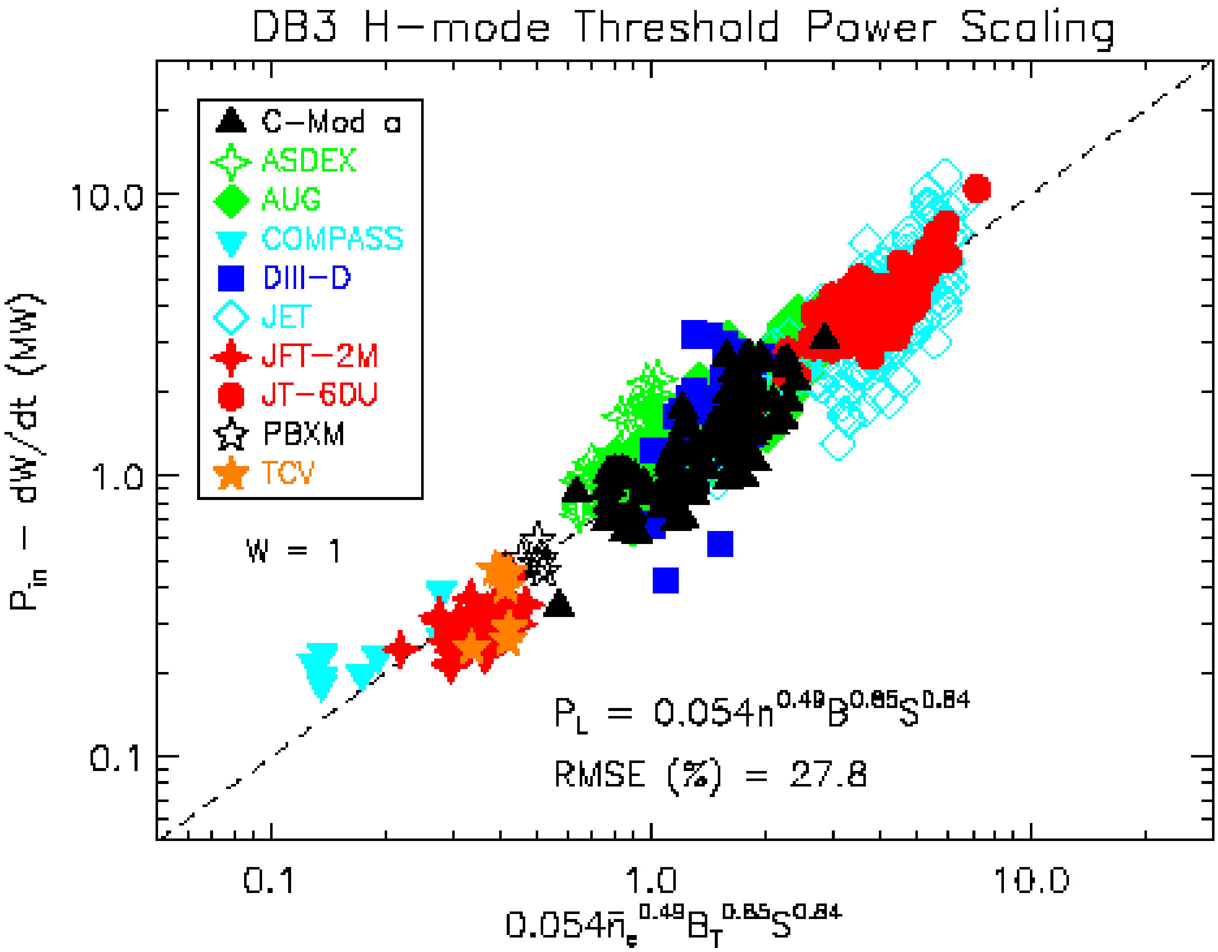


- Log-linear regression fit to L-H threshold data from all 10 tokamaks in the Threshold Database DB3 in D plasmas satisfying low threshold criteria (SELDB2)

- Equal weighting between points was used since equal weighting between tokamaks had somewhat higher RMSE

- Similar results obtained with κ included giving $\kappa^{0.33}$

- Including Kadomtsev constraint would increase RMSE by 5%



- Log-linear regression fit to L-H threshold data from all 10 tokamaks satisfying low threshold criteria (SELDB2) with line averaged density, toroidal field, and surface area in units of 10^{20} m^{-3}, T, m^2

- Equal weighting between points was used since equal weighting between tokamaks had somewhat higher RMSE

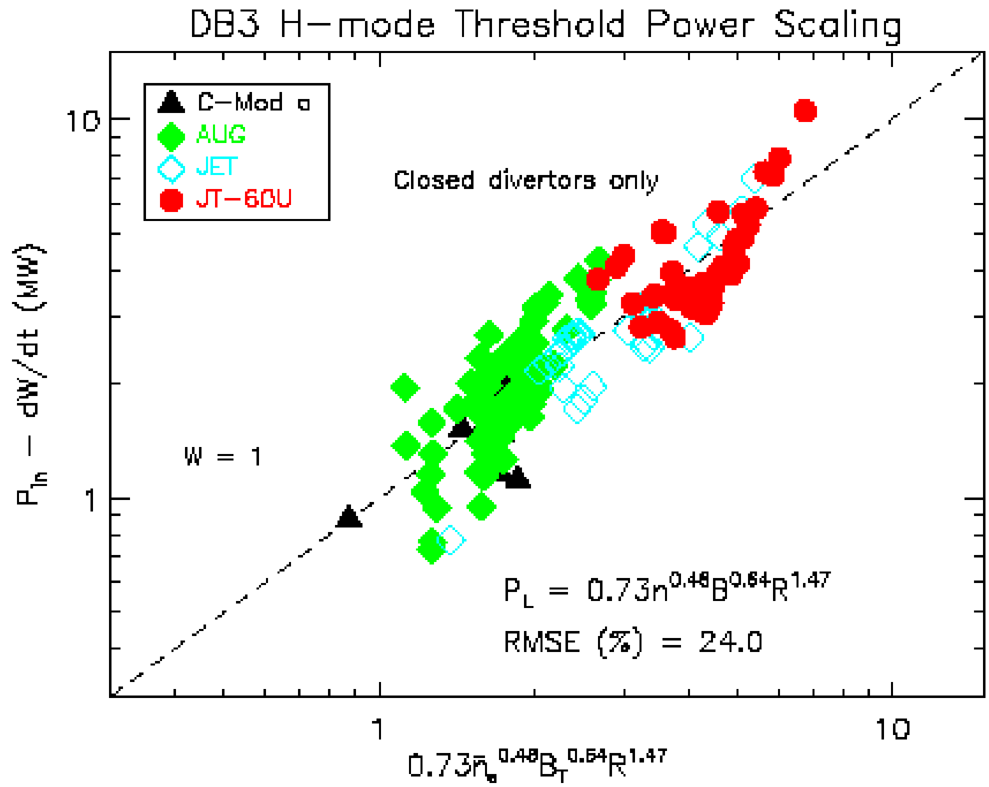
- Only D plasmas used though JET data show a 1/M dependence for hydrogen isotopes (H, D, T)

Cross-validation of the H-mode threshold scaling by removing one tokamak in turn and recalculating the resulting regression fit to the form:

$$P_L = C\,\bar{n}_e^{x_n}\,B_T^{x_B}\,R^{x_R}\,a^{x_a}$$

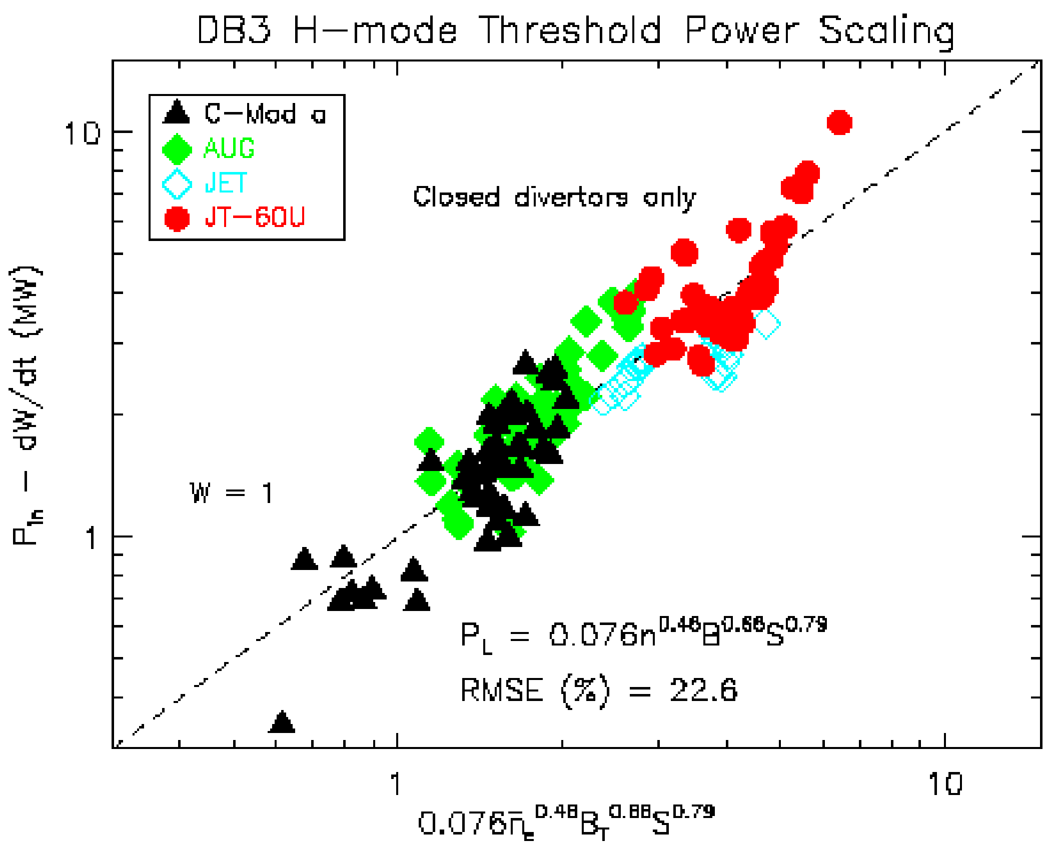
Tokamak (j)	Np (All-j)	RMSE All(j)	RMSE (j)	AVGE All(j)	AVGE (j)	RMSE (ALL)	RMSE (ALL -j)	C	x_n	x_B	x_R	x_a
ALL	702	26.8		3.6				1.42	0.58	0.82	1.00	0.81
C-Mod	583	24.1	25.4	-1.9	-38.8	32.7	26.3	1.49	0.59	1.05	0.75	0.84
ASDEX	665	24.2	24.3	17.3	22.7	26.8	26.7	1.62	0.61	0.79	0.93	0.90
AUG	578	20.4	20.8	11.7	17.4	26.9	27.5	1.23	0.51	0.90	0.95	0.80
COMPASS	694	18.0	18.6	52.0	63.8	26.9	26.4	1.30	0.61	0.83	1.11	0.76
DIII-D	630	29.6	29.9	13.8	19.4	26.9	26.2	1.19	0.63	0.82	1.20	0.66
JET	515	30.7	32.6	-1.1	-13.2	27.9	24.0	2.10	0.46	0.85	0.58	1.18
JFT-2M	640	15.4	14.8	-15.8	-32.6	28.0	26.3	1.19	0.55	0.73	1.17	0.55
JT-60U	621	20.0	21.0	4.4	8.0	26.9	27.5	1.56	0.64	0.77	1.02	0.83
PBXM	697	10.7	10.7	13.3	14.7	26.8	26.8	1.45	0.58	0.82	0.98	0.83
TCV	695	30.6	30.7	2.8	2.6	26.8	26.7	1.42	0.59	0.81	1.00	0.80
average	632	22.4	22.9	10.0	6.4	27.7	26.4	1.46	0.58	0.84	0.97	0.82

Closed Divertor H-mode Threshold Scaling



- Log-linear regression fit to L-H threshold data from only closed divertor data satisfying low threshold criteria with line averaged density, toroidal field, and major radius in units of 10^{20} m^{-3}, T, m
- Greatly reduced dataset compared to all 10 tokamak fits
- Reduced density, toroidal field, and size dependencies compared to 10 tokamak fits
- Predict considerably lower threshold powers for both a large and a compact high field next step device

Closed Divertor H-mode Threshold Scaling

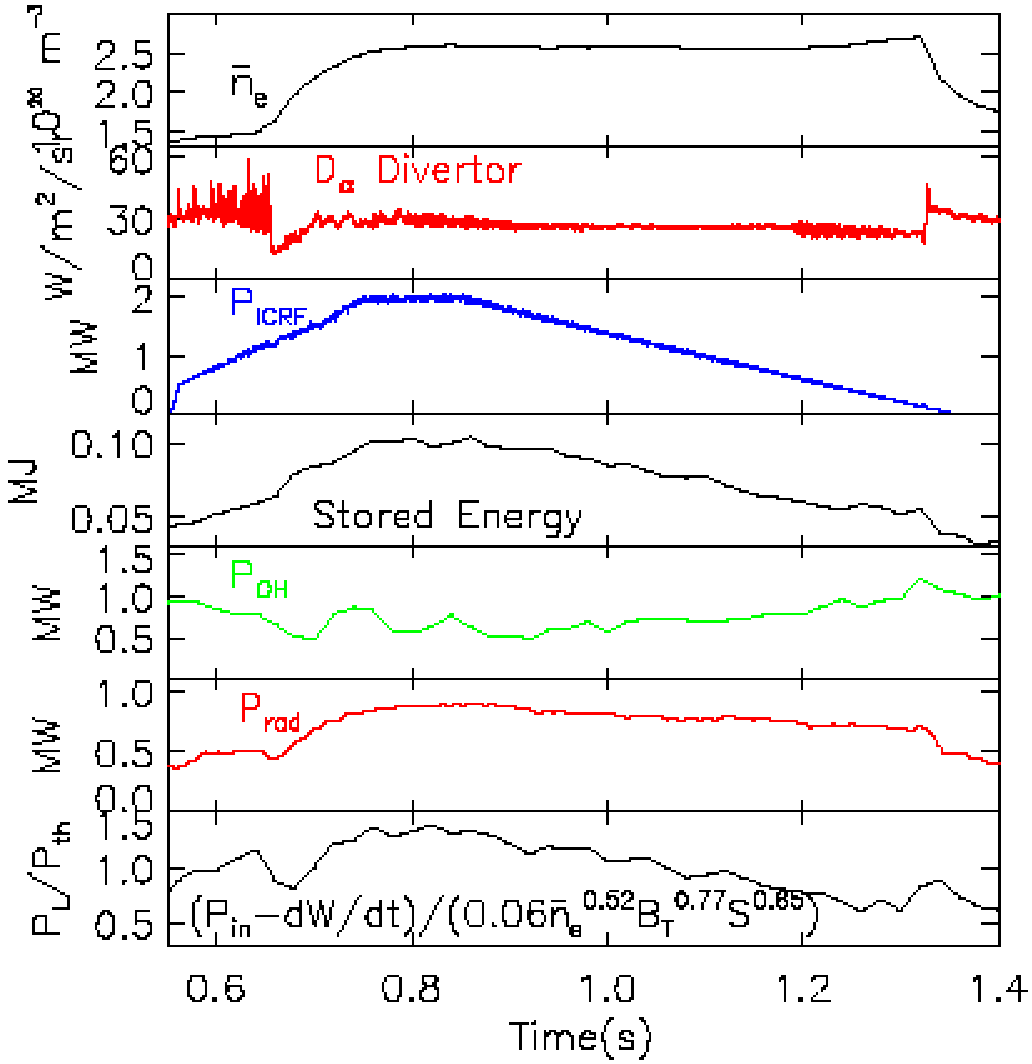


- Log-linear regression fit to L-H threshold data from only closed divertor data satisfying low threshold criteria with line averaged density, toroidal field, and surface area in units of 10^{20} m^{-3}, T, m^2

- Divertor geometry greatly affects the H-mode threshold both in individual machines and in the multi-machine regressions

- Reduced density and size dependencies compared to 10 tokamak fits

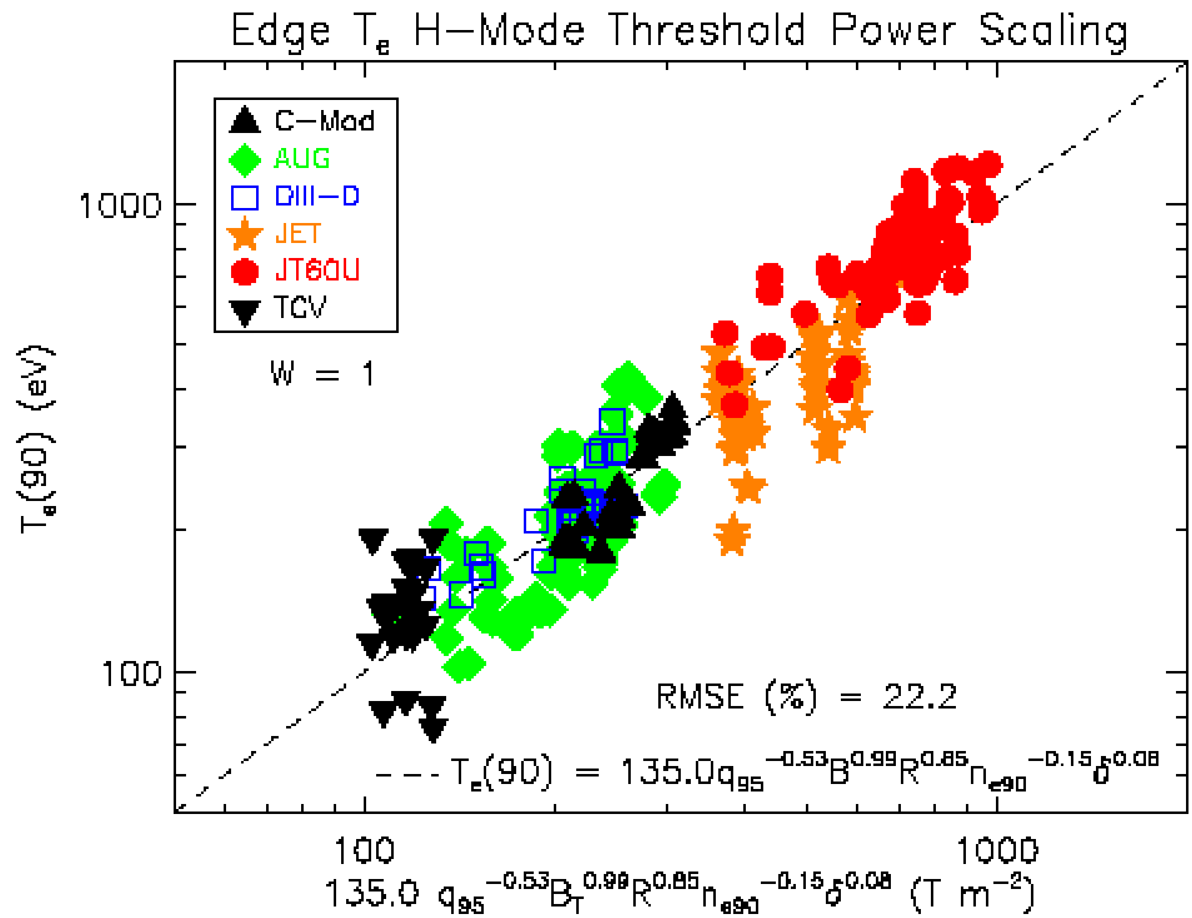
Hysteresis in the H-mode Threshold with Ramping P_{ICRF} on Alcator C-Mod



- Enters H-mode at $P_L/P_{th} = 1$ but remains in H-mode down to $P_L/P_{th} = 0.5$ as the density increases and P_{ICRF} decreases

- Particle confinement remains high down to $P_L/P_{th} = 0.5$ as the energy confinement returns to L-mode

- Such hysteresis is not observed on JFT-2M or JT-60U



- Only six tokamaks have edge temperature data in the threshold database (C-Mod, AUG, DIII-D, JET, JT-60U, TCV)

- Edge T_{e90} at the H-mode threshold increases with B_T and R with a weaker inverse dependence on q_{95} and n_{e90} and a small positive dependence on triangularity

- Scaling agrees with general trends observed in the data given the large uncertainties in the edge measurements

- Particle confinement remains high down to P_L/P_{th} = 0.35

- Energy confinement remains at about H_{89} = 1.6

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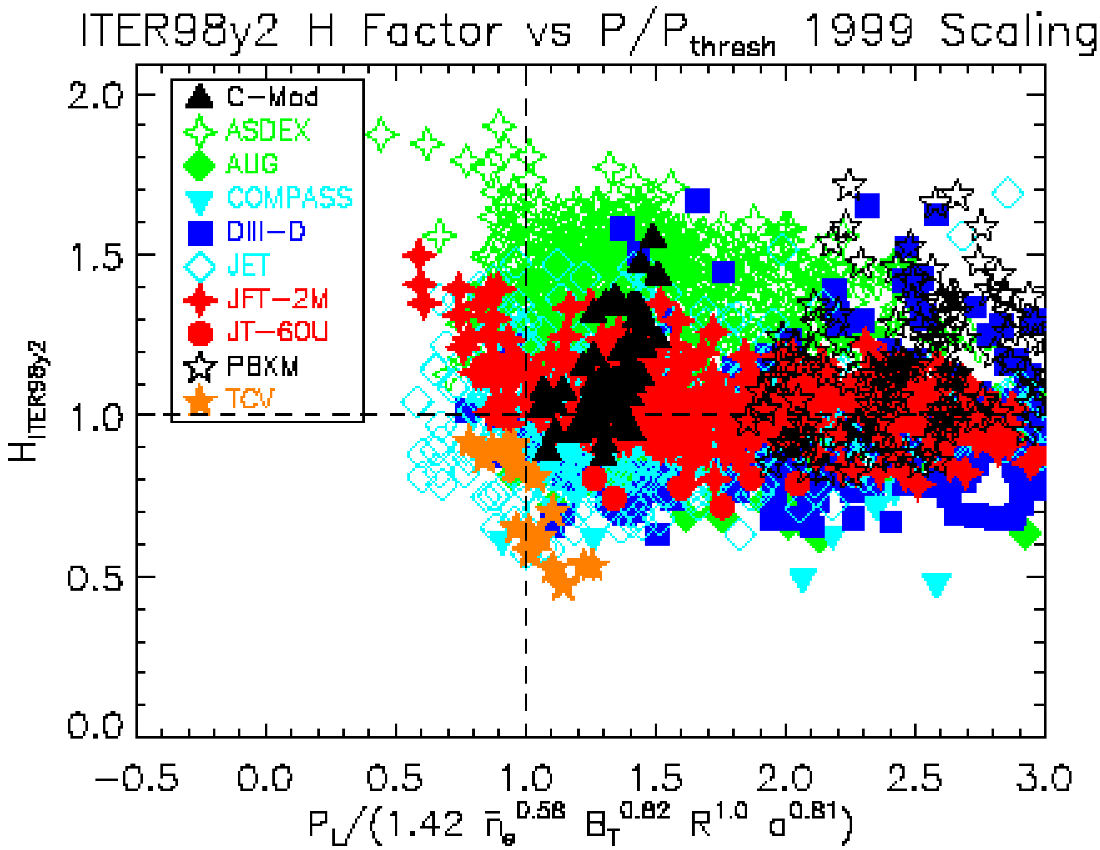
	FIRE	IGNITOR	ITER-FEAT
R (m)	2.0	1.32	6.2
a (m)	0.525	0.47	2.0
$\bar{n}_e$ (10^{20} m^{-3})	5.2 (6.2)	6.2	1.0
B_T (T)	10 (12)	13	5.3
S (m^2)	60	34	678
q_{95}	3	3.6	3.7
δ	0.4	0.43	0.33
n_{e90} (0.8 $\bar{n}_e$)	4.2 (5)	5.0	0.8
P_{aux} (MW)	30	24	73
P_{th}(nBRa)(MW)	23 (30)	19	49
P_{th}(nBS)(MW)	21 (27)	18	43
T_{e90th} (eV)	995 (1161)	800	1570

H-Mode Confinement Achievable at Power Levels Near the H-mode Threshold



- Good H-mode confinement (H98y2 > 1) achievable at power levels near the H-mode threshold scaling
- All H-mode points satisfying the standard selection criteria (SELDB3) in the H-mode confinement database are shown
- C-Mod, ASDEX, COMPASS, DIII-D, JET, JFT-2M, and TCV have points with H98y2 > 0.9 and $P_L/P_{th} < 1.1$

Conclusions

- Latest H-mode threshold scalings based on 10 tokamaks reduce the required threshold power compared to ITER FDR scalings
- Although there are $\times$ 2 uncertainties in the H-mode threshold, the present scalings indicate that FIRE, IGNITOR, and ITER-FEAT should be able to reach the H-mode at full parameters in DT
- Limited data from 4 tokamaks with closed divertors suggest that H-mode thresholds are lower for more closed divertors
- A factor of ~ 2 hysteresis in the H-mode threshold allows the plasma to remain in H-mode with increasing density and/or toroidal field
- Limited edge data from 6 tokamaks predict reasonable edge electron temperature thresholds for FIRE, IGNITOR, and ITER-FEAT
- H-mode confinement is achievable at power levels near the H-mode threshold scaling