First analysis of the updated ITPA global H-mode confinement database

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Global energy confinement scaling

- Extrapolate plasma performance to new machines (e.g. ITER)
- Reference for confinement in present experiments
- Boundary condition for numerical models
- Guidance for development of theoretical models
- Global H-Mode Confinement Database (°1989):
  - Presently under ITPA umbrella
  - DB4v5: data from 19 tokamaks
  - Version 3 (DB3, subset DB2v8) for IPB98(y,2) (1998)

$$\tau_{\mathrm{E,th}} = \alpha_0 I_{\mathrm{p}}^{\alpha_I} B_{\mathrm{t}}^{\alpha_B} \bar{n}_{\mathrm{e}}^{\alpha_n} P_{\mathrm{l,th}}^{\alpha_P} R^{\alpha_R} \kappa^{\alpha_\kappa} \epsilon^{\alpha_\epsilon} M_{\mathrm{eff}}^{\alpha_M}$$

$\tau_{\mathrm{E,th}}$: thermal energy confinement time (s)
I_{p}: plasma current (MA)
B_{t}: on-axis vacuum toroidal magnetic field (T)
$\bar{n}_{\mathrm{e}}$: central line-av. electron density (10^{19} m^{-3})
$P_{\mathrm{l,th}}$: thermal loss power (MW)
R: geometric major radius (m)
$\kappa = b/a$: plasma elongation ($= \mathrm{Area}/\pi a^2$ in IPB98)
ϵ: inverse aspect ratio
M_{eff}: effective atomic mass

Motivation and goals

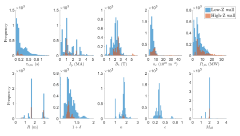
- Add data closer to ITER conditions and expand parameter range
- Add data from devices with fully metallic walls
- Improve reactor-relevant database coverage w.r.t. IPB98(y,2) (high n_e, low q_{95}, high β)
- Reconcile with single-machine scans (e.g. $\bar{n}_{\mathrm{e}}$, $P_{\mathrm{l,th}}$)
- Explore new predictor variables: e.g. triangularity δ (alternative to q_{95}/q_{cyl}), pedestal density, torque, …)
- Explore non-power law models (e.g. two terms)
- Robust regression analysis

Database update: DB5

- Addition of data from fully metallic devices (2017):
  - 627 time slices from JET-ILW (ITER-like wall) H-modes
  - 825 from ASDEX Upgrade (AUG) full W wall

} + C-Mod = **'High-Z' subset** (metal WALMAT, LIMMAT, DIVMAT)

- Improved fast-particle loss estimates (AUG)
- DB5v7: 13913 points from 19 devices
  - **STD5** (H-mode selection criteria): 7294 points
  - **STD5-SEL1** (q_{95}>2.8, 1.3<κ<2.2, ε<0.5, Z_{eff}<5: 5956 points)
  - **STD5-SEL2** (2.8<q_{95}<3.5, 1.6<κ<2.0, 0.28<ε<0.385 Z_{eff}<3): 1674 points)
- 200+ variables, added $n_{e,sep}$, $n_{e,SOL}$, torque (JET, AUG)



Histograms for the main scaling variables in STD5, with low-Z (carbon wall components) vs. high-Z (fully metal-wall devices).

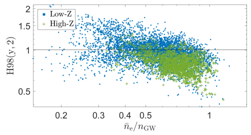
Device	DB5	STD3	STD5	STD5-SEL1	STD5-SEL2
ASDEX	1470	575	575	0	0
AUG-C	1590	755	1384	1377	193
AUG-W	825	0	767	767	69
C-Mod	87	82	82	82	11
COMPASS	43	21	21	21	14
DIII-D	670	502	502	497	64
JET-C	5069	1451	2235	2051	960
JET-ILW	627	0	600	591	363
JFT-2M	795	347	348	256	0
JT60-U	387	100	100	100	0
MAST	47	43	43	0	0
NSTX	252	230	230	0	0
PBXM	264	214	214	214	0
PDX	143	119	119	0	0
START	9	8	8	0	0
T10	12	4	4	0	0
TCV	21	17	17	0	0
TdeV	14	7	7	0	0
TEXTOR	1435	0	0	0	0
TFTR	104	2	2	0	0
TUMAN3M	49	36	36	0	0
Total	**13913**	**4513**	**7294**	**5956**	**1674**

Number of data points per tokamak in DB5, the standard set before the latest update (STD3), the current standard set (STD5) and two ITER-relevant subsets (ST5-SEL1 and STD-SEL2).

Statistic	$\tau_{E,th}$ (s)	I_P (MA)	B_T (T)	n_e (10^{19} m^{-3})	$P_{L,th}$ (MW)	R (m)	$1+\delta$	κ	ϵ	M_{eff}
Min.	0.0022 (0.014)	0.12 (0.17)	0.26 (0.94)	1.2 (1.2)	0.075 (0.38)	0.28 (0.67)	1.0 (1.0)	0.92 (0.93)	0.15 (0.15)	1.0 (1.0)
Max.	1.3 (1.3)	5.1 (5.1)	6.1 (5.8)	43 (43)	**33** (21)	3.4 (3.4)	1.9 (1.9)	2.6 (2.3)	**0.78** (0.40)	**3.9** (2.0)
Mean	0.19 (0.15)	1.4 (1.1)	2.1 (2.2)	5.8 (5.5)	7.0 (4.5)	2.1 (1.8)	1.3 (1.2)	1.7 (1.4)	0.32 (0.29)	1.9 (1.8)
Median	**0.11** (0.054)	**1.0** (0.62)	2.1 (2.2)	**5.1** (4.4)	**5.8** (2.8)	1.7 (1.7)	1.3 (1.2)	1.7 (1.6)	0.31 (0.29)	2.0 (2.0)
Stand. dev.	0.20 (0.20)	0.91 (1.0)	0.73 (0.71)	3.5 (4.9)	5.0 (3.7)	0.71 (0.55)	0.15 (0.19)	0.27 (0.39)	0.091 (0.064)	0.30 (0.30)

Summary statistics for the main scaling variables in STD5 (values in DB2v8 in parentheses).

Variables	ln I_p	ln B_T	ln n_e	ln $P_{L,th}$	ln R	ln $(1+\delta)$	ln κ	ln ϵ	ln M_{eff}
ln I_p	1	–	–	–	–	–	–	–	–
ln B_T	0.41 (0.39)	1	–	–	–	–	–	–	–
ln n_e	0.10 (0.19)	0.28 (0.36)	1	–	–	–	–	–	–
ln $P_{L,th}$	**0.83** (**0.85**)	0.40 (0.27)	0.25 (0.23)	1	–	–	–	–	–
ln R	**0.69** (**0.61**)	0.42 (0.01)	−0.32 (−0.49)	**0.63** (0.58)	1	–	–	–	–
ln $(1+\delta)$	0.36 (**0.63**)	−0.29 (0.01)	0.17 (0.33)	0.28 (0.59)	−0.02 (0.15)	1	–	–	–
ln κ	0.60 (**0.79**)	−0.11 (0.03)	0.30 (0.37)	0.55 (**0.76**)	0.12 (0.32)	**0.73** (**0.87**)	1	–	–
ln ϵ	0.49 (**0.79**)	−0.31 (0.25)	0.08 (0.18)	0.32 (**0.67**)	−0.10 (0.28)	0.52 (0.56)	0.58 (**0.65**)	1	–
ln M_{eff}	0.42 (0.59)	0.21 (0.26)	0.26 (0.27)	0.34 (0.57)	0.11 (0.26)	0.16 (0.33)	0.37 (0.51)	0.30 (0.47)	1



Confinement enhancement factor $\mathrm{H98(y,2)} = \tau_{\mathrm{E,th}}/\hat{\tau}_{98}$ *vs. Greenwald fraction* $\bar{n}_{\mathrm{e}}/n_{\mathrm{GW}}$ *for the STD5-SEL1 data set, highlighting the purely metallic devices. Overprediction is observed approaching the Greenwald limit*

Regression methods

- Complications arising in the analysis:
  - Heterogeneous data from multiple devices and diagnostics
  - Heterogeneous measurement uncertainties, log-transformation
  - Within-device vs. between-device variability
  - Model uncertainty
  - Uncertainty in predictor and response variables ($\tau_{E,th}$, $P_{l,th}$, ρ_*, ν_*, β, ⋯)
  - Predictor variable interdependencies (medium to strong collinearity)

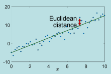
Parameter estimation techniques

- **Least squares** $\{\hat{\alpha}_k\} = \underset{\alpha_k \in \mathbb{R}}{\arg\min} \sum_{i=1} w_i^2 \left[y_i - f(\{x_{ij}\}, \{\alpha_k\})\right]^2$

$w_i \equiv 1$: ordinary least squares (**OLS**)

$w_i = \underbrace{\left(2 + \sqrt{n_J}/4\right)^{-1}}_{\text{IPB98(y,2) weights}}$: weighted least squares (**WLS**)

n_J = # points from device J

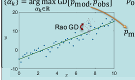


- **Geodesic least squares (GLS)**

$$\{\hat{\alpha}_k\} = \underset{\alpha_k \in \mathbb{R}}{\arg\max}\, \mathrm{GD}[p_{\mathrm{mod}}, p_{\mathrm{obs}}]$$

$$p_{\mathrm{obs}} = \prod_{i=1}^{n} \left[2\pi(\gamma_J y_i)^2\right]^{-\frac{1}{2}} \exp\left[-\frac{1}{2}\left(\frac{y - y_i}{\gamma_J y_i}\right)^2\right]$$

$$p_{\mathrm{mod}} = \prod_{i=1}^{n} \left[2\pi\left(\sigma_{y,i}^2 + \alpha_1^2 \sigma_{x,i1}^2 + \cdots + \alpha_m^2 \sigma_{x,im}^2\right)\right]^{-\frac{1}{2}} \times \exp\left[-\frac{1}{2}\frac{[y_i - (\alpha_0 + \alpha_1 x_{i1} + \cdots + \alpha_m x_{im})]^2}{\sigma_{y,i}^2 + \alpha_1^2 \sigma_{x,i1}^2 + \cdots + \alpha_m^2 \sigma_{x,im}^2}\right]$$



Regression analysis

Caveat: preliminary

Device	α_I	α_B	α_n	α_P	α_δ	α_κ	α_M	RMSE	R^2
ASDEX	0.69 ±0.11	0.13 ±0.16	0.68 ±0.08	−0.65 ±0.05	–	–	0.78 ±0.12	0.17	0.71
AUG-C	1.5 ±0.07	−0.26 ±0.08	0.033 ±0.037	−0.66 ±0.03	–	–	–	0.17	0.73
AUG-W	1.6 ±0.07	−0.30 ±0.09	0.055 ±0.057	−0.53 ±0.03	–	–	–	0.11	0.89
Alcator C-Mod	1.1 ±0.2	–	0.10 ±0.18	−0.60 ±0.15	–	–	–	0.10	0.79
DIII-D	1.1 ±0.09	0.080 ±0.11	0.10 ±0.06	−0.67 ±0.04	0.70 ±0.16	–	0.45 ±0.11	0.20	0.80
JET-C	1.1 ±0.04	0.16 ±0.04	0.31 ±0.02	−0.76 ±0.02	–	1.2 ±0.2	0.053 ±0.044	0.16	0.89
JET-ILW	1.1 ±0.1	−0.16 ±0.08	0.072 ±0.057	−0.57 ±0.03	–	–	0.40 ±0.05	0.11	0.86
JFT-2M	0.99 ±0.08	–	0.38 ±0.08	−0.86 ±0.04	–	–	0.11 ±0.06	0.10	0.93
JT60-U	0.78 ±0.29	0.47 ±0.38	−0.18 ±0.17	−0.35 ±0.13	–	–	–	0.14	0.83
MAST	1.1 ±0.9	–	0.17 ±0.30	−0.86 ±0.31	–	–	–	0.12	0.60
NSTX	0.29 ±0.14	1.2 ±0.2	0.58 ±0.15	−0.84 ±0.08	–	0.81 ±0.35	–	0.14	0.74
PBX-M	0.61 ±0.31	–	−0.073 ±0.086	−0.56 ±0.07	–	–	–	0.12	0.72
PDX	0.62 ±0.32	0.63 ±0.32	0.62 ±0.16	−1.1 ±0.15	–	–	–	0.18	0.68

- Scaling with I_{p} similar for ITER-like devices (C-Mod, DIII-D and JET), except AUG, but weaker for other machines
- B_{t} dependence weak in ITER-like devices, slightly negative in AUG
- Scaling with $\bar{n}_{\mathrm{e}}$ weak in ITER-like devices, slightly positive in JET-C. Stronger dependence in smaller or more circular devices
- Power degradation weakest in ITER-like devices

<u>ITER parameters used</u>: I_p=15 MA, B_T=5.3 T, n_e=10.3e19 m^{-3}, R=6.2 m, ε=a/R=0.32, κ=1.7, δ=0.33, M_{eff}=2.5, P_{heat}=87 MW

	α_0	α_I	α_B	α_n	α_P	α_R	α_κ	α_ϵ	α_M	$\hat{\tau}_{\mathrm{ITER}}$ (s)
IPB98(y,2)	0.0562	0.93	0.15	0.41	−0.69	1.97	0.78	0.58	0.19	3.62

STD5 (ELMy + ELM-free)

95% confidence intervals

Method	α_0	α_I	α_B	α_n	α_P	α_R	α_κ	α_ϵ	α_M	$\hat{\tau}_{\mathrm{ITER}}$ (s)
OLS	0.049 ±0.002	1.1 ±0.02	0.085 ±0.020	0.19 ±0.02	−0.71 ±0.01	1.5 ±0.04	0.80 ±0.04	−0.043 ±0.046	0.25 ±0.03	2.7 ±0.1
WLS	0.040 ±0.002	0.99 ±0.03	0.11 ±0.02	0.29 ±0.02	−0.64 ±0.01	1.7 ±0.04	0.79 ±0.04	0.093 ±0.046	0.25 ±0.03	2.9 ±0.1
GLS	0.042 ±0.003	1.2 ±0.02	0.068 ±0.016	0.21 ±0.01	−0.78 ±0.01	1.6 ±0.03	0.88 ±0.06	−0.052 ±0.027	0.47 ±0.07	2.7 ±0.03

Strongest power degradation and isotope effect

W.r.t. IPB98(y,2) (ELMy):
- Stronger dependence on I_{p}, weaker on B_{t}
- Weaker dependence on $\bar{n}_{\mathrm{e}}$ and R
- No dependence on ϵ (but different κ definition)
- ITER predictions up to 25% lower

STD5-SEL1

Considerable uncertainty

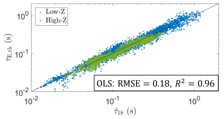
Method	α_0	α_I	α_B	α_n	α_P	α_R	α_κ	α_ϵ	α_M	$\hat{\tau}_{\mathrm{ITER}}$ (s)
OLS	0.045 ±0.005	1.3 ±0.03	−0.10 ±0.04	0.13 ±0.02	−0.71 ±0.01	1.2 ±0.06	1.1 ±0.1	−0.32 ±0.05	0.24 ±0.04	2.6 ±0.1
WLS	0.030 ±0.005	1.3 ±0.04	−0.069 ±0.056	0.19 ±0.05	−0.64 ±0.03	1.3 ±0.1	1.3 ±0.2	−0.46 ±0.08	0.094 ±0.055	3.0 ±0.2
GLS	0.023 ±0.007	1.3 ±0.04	−0.018 ±0.067	0.17 ±0.03	−0.79 ±0.02	1.5 ±0.1	1.9 ±0.4	−0.38 ±0.08	0.33 ±0.13	2.5 ±0.1

W.r.t. STD5: shape dependence varies

STD5-SEL1 (shape: δ, κ, ϵ)

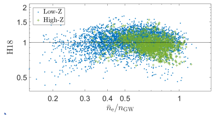
'H18'

Method	α_0	α_I	α_B	α_n	α_P	α_R	α_δ	α_κ	α_ϵ	α_M	$\hat{\tau}_{\mathrm{ITER}}$ (s)
OLS	0.036 ±0.003	1.3 ±0.03	−0.07 ±0.03	0.12 ±0.02	−0.70 ±0.01	1.3 ±0.1	0.63 ±0.06	1.1 ±0.1	−0.34 ±0.05	0.27 ±0.03	2.6 ±0.1
WLS	0.021 ±0.002	1.3 ±0.03	−0.055 ±0.029	0.20 ±0.02	−0.65 ±0.01	1.3 ±0.1	0.78 ±0.06	1.3 ±0.1	−0.49 ±0.04	0.10 ±0.03	3.1 ±0.1
GLS	0.020 ±0.005	1.3 ±0.04	−0.03 ±0.04	0.14 ±0.02	−0.76 ±0.01	1.4 ±0.1	0.72 ±0.05	1.7 ±0.3	−0.42 ±0.07	0.41 ±0.07	2.6 ±0.1



Moderate dependence on δ

Confinement enhancement factor $\mathrm{H18} = \tau_{\mathrm{E,th}}/\hat{\tau}_{18}$ *vs. Greenwald fraction for STD5-SEL1 (GLS).*



Conclusions and outlook

- Ongoing revision and analysis of global H-mode confinement database
- Recently added data from devices with fully metallic walls (more devices might contribute)
- Single-device scalings vary considerably between machines, ITER-like devices more favorable
- Comparison with IPB98(y,2) reveals some differences (subject to further analysis):
  - Generally weaker dependence on toroidal field and density
  - Noticeable influence of plasma triangularity on confinement
- Future analysis to focus on data and variable selection, model comparison, treatment of data subsets (e.g. weighting) and robustness, scaling with dimensionless variables

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