Next Step Tokamak Physics: Confinement-oriented Global Database Analysis

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Abstract. We describe and analyse an international multi-tokamak confinement database, both motivated by physics and with a view toward prediction of next-step burning-plasma experiments such as ITER. Significant additional ohmic and L-mode data have been assembled from several tokamaks, which has resulted in the 'ITERL.DB2' dataset. Simple density-roll-over scalings are presented for ohmic confinement. For H-mode, the confinement time in the essentially enlarged data set ITERH.DB3 is compared with the ITERH-98P(y,2) reference scaling. A distinction is made between discharges with and without heavy gaspuff. Beyond a standard power-law scaling, the empirical 'influence' on confinement of q_{95}/q_{cyl}, directly related to triangularity, and of the global density peaking factor (for L- and H-mode) is quantified. A log-linear quadratic formula is given which describes physically more precisely than ITERH-98P(y,2) the relation between the isotope effect and the heating power degradation of confinement, while predicting a similar thermal confinement time for ITER ($\tau_{E,th} \simeq 3.5$ s.). Based on a recently provided plasma edge dataset, 'E.1', separate scalings of the plasma core and pedestal energy are derived. Finally, a class of nonlinear scalings is discussed which are suitable, in contrast to offset (non-)linear models, to fit roll-over dependence, and, simultaneously, the scaling of L-mode and H-mode confinement.

1. New features of the Ohmic, L and H-mode Confinement Databases. The ITER.LDB2 ohmic and L-mode database [SK97] has been substantially updated by ohmic data from ASDEX, FTU, JET, T10, and from the additional tokamaks Alcator-C, FT, and RTP as well as by new L-mode data from ASDEX, DIII-D, FTU, RTP, T10, and Tore Supra. Large additions stem from Alcator-C ($N \simeq 625$, OH), ASDEX ($N \simeq 360$, OH, $N \simeq 160$, L), FT($N \simeq 200$, OH) and JET($N = 2300$, OH), where N denotes the approximate number of timeslices in the standard 'working' dataset. [The

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exact numbers are available in the database description.] The variable list has been revised and extended, attaining full compatibility with the final version of the new DB3 H-mode Confinement Dataset. It now contains, among others, cross-link indicators to public versions of the H-mode confinement, Threshold, Profile and Edge ('Pedestal') Datasets, from which one can get a quick impression of the availability of 'common subsets' of the database, even if the other datasets are not 'online' available in an MS-SQL environment.) Following literary tradition, the new ohmic and L-mode dataset is coined ITERL.DB2. The selection rules to obtain the standard ('working') dataset have also been revised, the main ones being: 'Semi-stationarity', 'nohelium', 'l_i below 2', and '$\gamma_T = T_i(0)/T_e(0)$ between 0.4 and 2.5'. The last criterion is a practical compromise to preclude discharges which are clearly 'hot-ion' or 'hot-electron'. Furthermore, 'duplicate observations' have been deselected [OK99]. The main division is between ohmic and (standard) L-mode. Enhanced performance (EP) discharges are considered for comparison. The thermal energy, W_{th}, is based on either kinetic measurements (Alcator C/C-Mod, JT-60U, FT/FTU, RTP, TFTR, T-10, START) or magnetic measurements with correction for fast particles (ASDEX, DIII(-D), JET, JFT-2M, PBX-M, PDX, TdeV, T-10, Tore Supra). Table 1 presents ohmic log-linear regression coefficients of W_{th} against I_p, B_t, $\overline{n}_e$, and $\overline{n}_e \otimes \overline{n}_e$, the latter expression denoting a log-quadratic model [OK89] with respect to density, which is intended to detect the presence of density roll-over, and not as a final model for the true functional dependence. The isotope effect and $Z_{\rm eff}$ play an additional, intriguing, role, see [ES96]. In Table 1, $N(H,D)$ denotes the number of time-slices from hydrogen and deuterium discharges, respectively. The (negative) curvatures in this table are statistically significant (3-6 std. dev.). It is noted that the column $\overline{n}_{e,20}$ gives the effective density exponent at $10^{20} m^{-3}$, which is a substantial extrapolation for JET. (For JET, $\langle n_{e,20} \rangle$ has been used instead of $\overline{n}_{e,20}$.) For L-mode and H-mode, density roll-over is not so universally present as for ohmic discharges. The tokamaks JET, ASDEX and C-Mod have provided data to clarify systematic differences between W_{th} from W_{kin}, W_{mhd} and W_{dia}. As for H-mode, review sheets are available in a substantial number of cases. As an example of error-propagation information we cite C-Mod: "The sources of error in W_{kin} are $T_e(r) : 5-10\%$, $\overline{n}_e(r) : 5-10\%$, Vol $: 3-5\%$, $P_{oh} : 3-5\%$, $T_i(0) : 10\%$, which gives, while assuming $T_i(r)/T_e(r)$ is constant, a composite error in W_{th} of 13-19%." Besides the ITER89-P scaling for the total ('engineering') L-mode confinement time, we mention [HS95, SK97] for thermal confinement, and do presently not propose an alternative scaling.

Since ITERH.DB3v5 [KT98, IPB99], substantial new ELMy H-mode data have been assembled by ASDEX Upgrade (D into D and H into H) and JET (H, D and T). Interesting new data were also provided by DIII-D and by the new tokamaks START (UK), TdeV (Canada), TUMAN-3M and T10 [NK00]. A particularly well-evaluated dataset ($N \simeq 50$) has been provided by JT-60U. In addition, review sheets have been provided for a number of TFTR discharges included in the new (extended) standard dataset. The scaling ITERH-98P(y,2), improving upon ITERH-92P(ELMy)

Table 1: OHMIC THERMAL ENERGY CONFINEMENT SCALINGS

TOK	$N(H,D)$	*rmse*	C	I_p	B_t	$\overline{n}_{e,20}$	$\overline{n}_{e,20} \otimes \overline{n}_{e,20}$
Alcator-C	(79,546)	0.15	0.038	1.10	–0.29	0.74	–0.053
ASDEX	(48,328)	0.14	0.106	0.85	0.17	0.23	–0.093
FT	(0,199)	0.09	0.028	0.98	0.19	0.56	–0.110
FTU	(11,107)	0.08	0.032	0.79	0.30	0.42	–0.065
JET	(0,2316)	0.18	0.280	0.96	0.39	–0.24	–0.171
JT-60U	(139,0)	0.08	0.410	0.83	0.28	0.43	–0.056

and ITERH-93P(ELM-free), is presently accepted as reference for ITER FEAT [GJ00]. It is based on the medium-sized to large tokamaks, and uses $\kappa_a = V/2\pi^2 Ra^2$ instead of $\kappa = b/a$, which accounts for the position of PBX-M and leads to a more adequate aspect ratio dependence. It has been based on a $N = 1310$ standard ELMy dataset, see [IPB99]. In the new database, DB3 (final), a restricted ('excl. gaspuff, TFTR, and ohmic H-mode') and an extended ('incl. gaspuff, TFTR, and ohmic H-mode') standard ELMy dataset has been defined, without restricting the type of additional heating. Fig. 2 shows the observed $\tau_{E,th}$ for the extended dataset against the prediction by ITERH-98P(y,2). The numbers along the tokamaks on the plot indicate: (I) the number of data on which ITERH-98P(y,2) was based, (II) the additional data in the restricted standard ELMy dataset ($N = 2044$), (III) the additional data in the extended ELMy standard dataset ($N = 2678$). (JET is notably affected by the heating method and AUG by the gaspuff selection criterion.) T-10 and TUMAN-3M provided ELM-free data (not on plot). In the plot, $\langle$dev.$\rangle$ denotes the average deviation and rmse the root mean-squared error of all data w.r.t. ITERH-98P(y,2). The confinement-time extrapolations on the plot ('required against predicted') pertain to ITER FEAT ($Q = 10$) and ITER FDR ($Q \simeq 100$), respectively. From the plot one can see that ITERH-98P(y,2) well predicts the additional data, including –post hoc– those from the tight aspect-ratio START machine [RA00]. The large scale and the one-dimensional structure of the plot should not mask the fact, however, that the practical approximation by a simple power law is limited by the fact that the true functional dependence may well contain non-linearities (on logarithmic scale). This has been realized since more than a decade, and various log-linear interaction models offset-(non-)linear models have been fitted to the data, see [IPB99] and the references therein. A particular type of log non-linear dependence has been advocated [DK96], scientifically not entirely unjustified, even if such types of curvatures were in part satellitic, being effectuated by systematic differences between W_{th} based on W_{mhd} and W_{dia}, respectively, and for another part decomposed into their constituents [OK99]. The ITER confinement-time interval estimate ($\pm$20% for ITER FEAT) takes the prediction range of such log non-linear dependencies into account, see [IPB99] and [OK99].

2. H-mode Confinement Relative to ITERH-98P(y,2) and Log-Linear Interaction. *Density peaking:* The 'influence' of density peaking on confinement, in addition to that described by the usual empirical simple power-laws, does not give a unified picture. However, the underlying physics is expected to be interesting in relation to L-mode and enhanced performance regimes. In a first analysis, for ELMy H-mode the exponent of the density peaking factor, $\gamma_n = 0.5 * (n_{e,0}/\overline{n}_e + \overline{n}_e/\langle n_e \rangle)$, in addition to ITERH-98P(y,2), is large (1.5 ± 0.3) for ASDEX Upgrade and C-Mod, but weak (0.2 ± 0.1) for JET and DIII-D and almost not existent for ASDEX. For L-mode, compared with the ITER-89P scaling (with $\overline{n}_e^{0.1}$), the additional exponent of γ_n is strong ($\simeq 1.0$) for T-10 and RTP (only a limited number of timeslices), medium ($\simeq 0.5$) for C-Mod, DIII-D and JFT-2M, close to zero for JET, JT60, TFTR and Tore Supra, and slightly negative ($\simeq -0.25$) for ASDEX and PDX. However, when we compare with ITERH-98P(y,2), with a similar density dependence, $\overline{n}_e^{0.4}$, as in thermal L-mode scalings [HS95, SK97], the exponent of γ_n tends to be ($\simeq +0.5$) larger. On average, we obtained the L-mode peaking factor exponents $\gamma_n(98y2) = +0.25$ and $\gamma_n(89) = -0.25$, respectively. Part of this difference may be explained by the fact that $\overline{n}_e$ and γ_n are negatively correlated ($r = -0.5$ on log scale). Stationarity of the density profiles and edge density peaking need further investigation. *Various confinement scaling issues:* At the time of writing a satisfying fit describing density roll-over as a function of triangularity for heavy gaspuff discharges and at the same time predicting the other tokamaks well (in particular C-Mod) has not been found, but investigations in this direction are continuing. It is interesting to consider edge density or recycling flux in addition to $\overline{n}_e$ [AK99]. Sometimes, the question is raised whether beta-limit discharges with reduced confinement contaminate the standard dataset. A selection criterion to exclude beta-limit shots has been set since the first release of the database, see [KT94], and the confinement time prediction for ITER by ITERH-98P(y,2) and its predecessors is for 'standard' ELMy H-mode, without degradation by resistive MHD activity ('NTMs'). Another issue is that the scaling, expressed in dimensionless variables shows a negative β dependence, in contrast to single scans [CP98]. This question is (only) partly solved by the different estimates that follow from minimising the sum of squares in different directions, discussed in [OK99] to explain the difference in heating power degradation of the confinement time according to single scan experiments and global scaling. *Scaling according to log-linear interaction model:* A simple power-law fitted to the new H-mode database is very similar to ITERH-98P(y,2), and does not need further mentioning. Deviations from log-linear scalings can be detected by quadratic terms on log scale ('interaction models') [OK92]. They are also easily fitted. In practice, however, only a few terms survive statistical significance and subsequent practical physical evaluation. For the extended ELMy dataset, while omitting both ohmic H-mode and PBX-M ($N = 2593$), the interaction term $0.165(\log M_{\mathrm{eff}} \log P_{L'}/\overline{n}_{e,20}V)$ is significant, cf. [OK92]. The remaining factor is $W_{th} \sim I_p^{0.95} B_t^{0.175} \overline{n}_{e,20}^{0.5} P_{L'}^{0.16} R^{2.3} (a/R)^{0.7} \kappa_a^{0.8} M_{\mathrm{eff}}^{0.35} (q_{95}/q_{cyl})^{0.6}$. The scaling, with rmse = 15.3%, leads to $\tau_E = 3.45$ s. for ITER FEAT, and is to be considered as a physical refinement (not as a practical replacement) of ITERH-98P(y,2). The persistent factor $(q_{95}/q_{cyl})^{0.6}$ indicates an influence of plasma shape and/or shear [OK99]. It should be stressed that the prediction for ITER is under the condition that the L-H power threshold is exceeded [JS00] and H-mode operation at, say, 0.85 of the Greenwald density is possible.

3. Separate Scaling of Plasma Core and Plasma Pedestal Energy. To improve simple power-law scalings, pedestal data for H-mode from the Edge Database, see [MS00], have been provided by representatives of the AUG,C-Mod,DIII-D,JET and JT-60U teams, consisting of (40,16,16, 140/90,50) time slices, respectively. The basic variables are pedestal energies, densities and temperatures, in general for the electrons, for DIII-D [GR97] and JT-60U also for the ions. The ELMy subset of Edge Dataset intersected with H.DB3 is called called E.DB1. While restricting attention to the subset with non-missing $T_{e,ped}$ and without heavy gaspuff ($N = (4,7,10,55,50)$) one obtains the following preliminary scaling when not using C-Mod ($N = 119$): $W_{ped} \sim I_p^{2/3} \overline{n}_e^{0.5} P_{L'}^{2/3} V^{0.8} M_{eff}^{0.5}$, with a rmse about 22%. The isotope dependence stems mainly from the JET data. Similarly, $n_{e,ped} \sim I_p^{-0.1} \overline{n}_e^{1.25} V^{0.25}$ with a rmse=8%. (Evidently, $W_{ped} \simeq 2W_{ped,e} \sim n_{e,ped} T_{e,ped} V$.) Substituting $P_{L'}$ by $T_{e,ped}$ gives the (almost trivial) empirical relationship $W_{ped} = T_{e,ped} \overline{n}_e^{1.1} V^{1.1}$. An interesting scaling without $\overline{n}_e$ is $W_{ped} \sim I_p^{1.5} M_{eff}^{1/4} T_{e,ped}^{1/4} V^{1/3}$. Addition of gaspuff data (AUG,JET), while adding C-Mod and otherwise restricting attention to type-I ELM's only, leads to a scaling of W_{ped} with a less pronounced power and volume dependence:

$$W_{ped} \sim I_p^{1.7\pm0.5} B_t^{0.4\pm0.25} \overline{n}_e^{0.0\pm0.3} P_{L'}^{0.2\pm0.2} V^{0.5\pm0.3} M_{\mathrm{eff}}^{0.5\pm0.4} (q_{95}/q_{cyl})^{(5/3)\pm1}$$

with N=(36,7,10,68,28) and a rmse $\simeq$ 30%. Because of data collinearity, the exponents of I_p and M_{eff} have been imposed (within 2.5 std. dev.) based on an additional AUG scan [JN00], and on the JET subset, respectively, while no dependence on $\overline{n}_e$ was assumed. The indicated two standard deviation errors (from OLS) are substantial. In summary, the presently *preliminary*. E.DB1 dataset allows a variety of simple empirical scalings, which are more suitable for interpolation than for extrapolation. Additional, reliable data from several tokamaks are required for more accurate estimation. The scaling of $W_{th,e}/W_{th,i}$ deserves further investigation and magnetic shear is a possible hidden variable [MS00].

4. Towards Non-Linear Confinement Scalings and Unification. In the past, special attention has been devoted to offset-(non-)linear scalings, where the thermal energy, W_{th} is expressed as the sum of two-term power-law expressions, with one term (the 'offset') independent of the heating power, see [IPB99]. However, two-term power-law scalings have a clear deficiency in that they are unable to describe roll-over effects since, on a logarithmic scale, for high values of a physical parameter (e.g. density $\overline{n}_e$), the higher of the two corresponding exponents in the scaling becomes predominant. Hence, for two-term scalings, $\log(W_{th})$ is a convex function of each plasma parameter, whereas roll-over (e.g. observed near the Greenwald limit), corresponds to a concave dependence. Therefore, one is almost bound to consider the following extended class of non-linear scalings: $W_{th} = (P1 + P2 + P3)/(1 + P4)$, where $P1, \cdots, P4$ are simple power-law expressions in the basic plasma parameters. Obviously, a judicious choice and drastic simplifications are to be made, a process called 'Occam's razor' in [RP99], where a three-term power-law scaling $(P4 = 0)$ in 'dimensionless' plasma parameters has been fitted to W7-AS data. The physical rationale is that not only the thermal energy, but also the loss power across the separatrix, $P_{L'} = P_{L',e} + P_{L',i}$ is an additive quantity. In addition to $\tau_E = \tau_{E,1} + \tau_{E,2}$ for offset-linear scalings, the formula allows, for P3=0, to fit $\chi_{\text{eff}} = \chi_e + \chi_i$ with $\chi_{\text{eff}} \simeq a^2/\tau_E$, and otherwise even, $\tau_E = (W_{core,e} + W_{core,i} + W_{ped})/(P_{L',e} + P_{L',i})$. This line of investigation requires an extensive non-linear fitting approach and resolution of collinearity aspects, especially in the case that a simple power-law model already gives a good fit. Results of our experience to fit this type of models to (I) ELMy confinement near the Greeenwald limit, (II) non-linear density dependence from stiff to non-stiff profile regimes as a function of plasma edge temperature, (II) L-mode and ELMy H-mode confinement simultaneously are due to be reported in the foreseeable future.

It is noted that model (I) does not allow for multiple-value cusp-type response functions with hysteresis which are even more complicated to fit [OK96]. However, it agrees with a mesoscopic transition model [I&I96], and an experimental suggestion from AUG [IPB99] and from JFT-2M in ITERL.DB2, that the transition from L-mode to H-mode can sometimes be smooth when the input power is varied gradually (from shot to shot).

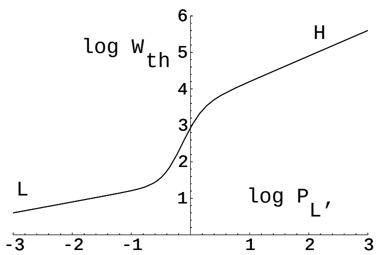

Figure 1: *Theoretical shape of (P1+P2)/(1+P3) (1-D section, e.g. $y = \log W_{th}$ vs $x = \log P_{L'}$ or $\log \overline{n}_e$) to describe L- and H-mode confinement.*

Finally, it is noted that the separate power-law expressions in the above model $(P3 = 0)$ describe planes in (logarithmic) plasma parameter space. Fitted to L-mode and H-mode data jointly, the intersection of these planes is near the transition region of the L-H (H-L) confinement, see Fig. 1 (indicative for e.g. the power or density dependence of W_{th}). Hence an interesting connection exists with H-mode threshold power analysis [JS00].

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References

[IPB99] ITER Physics Basis Document, Nuclear Fusion **39** (1999) 2232.

[GJ00] G. Janeschitz et al., Nuclear Fusion **40** (2000) 1197.

[OK92] O. Kardaun for the H-mode Database Working Group (1992), IAEA Würzburg, 251.

[KT94] K. Thomsen for the H-mode Database WG, Nucl. Fusion **34** (1994) 131.

[TT96] T. Takizuka for the Confinement Database and Modeling WG (1996), IAEA Montreal, 795.

[KT98] K. Thomsen et al. (1998), IAEA Yokohama, 987.

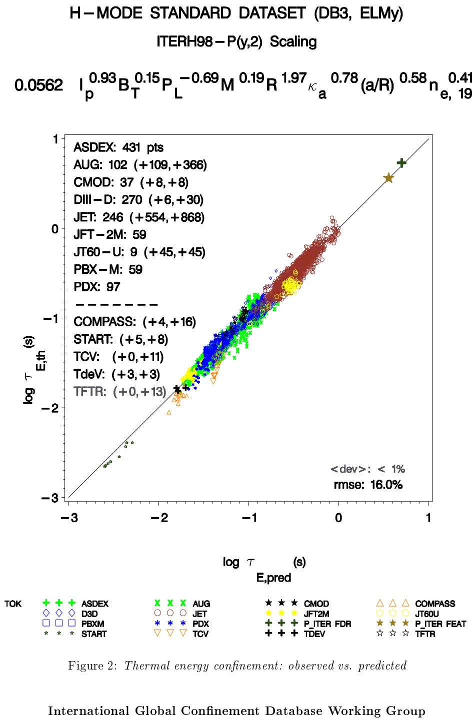

Figure 2: Thermal energy confinement: observed vs. predicted

[OK99] O. Kardaun, Plasma Phys. Control. Fusion **41** (1999), 429.

[JS00] J. Snipes for the International H-mode Threshold Database WG, Plasma Phys. Control. Fusion, **42** (2000) A299.

[SK97] S. Kaye for the ITER Confinement Database WG, Nucl. Fusion **37** (1997), 1303.

[MS00] M. Sugihara, et al., Nucl. Fusion **40** (2000), 1743.

[GR97] C.M. Greeenfield et al., Nucl. Fusion **37** (1997), 1215.

[US95] U. Stroth et al., Nucl. Fusion **35** (1995), 131.

[NK00] N.A. Kirneva et al. (2000), EPS Budapest, paper OR26.

[ES96] E. Simmet and the ASDEX Team (1996), Plasma Phys. Control. Fusion **38** 689.

[RA00] R. Akers et al., Nucl. Fusion **40** (2000), 1223.

[OK96] O. Kardaun et al. (1996), Computational Statistics XII (Barcelona), Vol I, 312.

[BT97] G. Bracco, K. Thomsen, Nucl. Fusion **37** (1997), 759.

[DK96] W. Dorland et al. (1996), in: Proc. Combined ITER Transport, Confinement Database and Modeling Workshop (Oct. 13, Montreal), see also: J. Glanz et al., Science **274** (1996) 1602, D. Baldwin et al. Science **275** (1997) 289.

[I&I96] K. Itoh and S.-I. Itoh (1996), Plasma Phys. Control. Fusion **38** 1.

[CP98] C. Petty et al., Physics of Plasmas **5** (1998) 1695.

[OK89] O. Kardaun et al. (1989), EPS Venice, Vol I, 253.

[HS95] H. Shirai et al. (1995), IAEA Seville, 355.

[AK99] A. Kallenbach et al. (1999), Plasma Phys. Control. Fusion **41** B177.

[RP99] R. Preuss, V. Dose, W. von der Linden, Nucl. Fusion **39** (1999) 849.

[JN00] J. Neuhauser for the ASDEX Upgrade Team (2000), in: Proc. Combined ITER Pedestal, Divertor, MHD, Disruption and Control Workshop (Oct. 13, Garching).