Abstract Submitted
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A Model for the Energy Confinement Scaling of H-mode Plasmas in Tokamaks[1] C.L. HSIEH, B.D. BRAY, J.C. DEBOO, T.H. OSBORNE, General Atomics — ITER96L and ITER98Hy are two examples of deducing from experimental data the scaling of energy confinement time for the L–mode and H–mode plasmas. Even though they represent different plasma operation regimes, the scaling laws show similar characteristics. These may be taken to imply strong connections between the heat transport of H and L regimes. For instance, the regimes may share the same thermal diffusivity in the plasma interior. A model is being developed based on the idea that an H–mode plasma is simply a much larger L–mode plasma with its boundary truncated in order to fit the machine physical size. In other words, an H–mode plasma is an L-mode with some unusual boundary conditions, and its confinement scaling ought to be the L–mode scaling modified by the effects from the new boundary conditions. The model estimates the boundary conditions, taking hints from the differences between ITER96L and ITER98Hy. As a result of these trials, the model creates a number of H–mode confinement scaling expressions in functional forms different from that of ITER98Hy.

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☐ Prefer Oral Session
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C.L. Hsieh
hsieh@gav.gat.com
General Atomics

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I. INTRODUCTION

- **H–mode: two different viewpoints**

  — **H and L are two different types of plasma — the thermal diffusivity χ_H is not the same type as χ_L. For instance, Gyro-Bohm type versus Bohm type. The plasma edge pedestals define an offset part of the plasma stored energy W_o**

  — **H and L are the same type of plasma — χ_H is the same as χ_L. There is no change in the mechanism of heat transport in the plasma interior. The difference is the plasma boundary condition. Or, an H–mode plasma can be considered as a larger L–mode plasma with its boundary truncated to the machine size**

- τ_E^H: three ways to express the energy confinement scaling

  - Conventional: τ_E^H ~ power law of plasma global parameters

  - Offset non-linear (Takizuka, T):

$$W_{TH} = W_O + \tau_{INC} P_L,$$

where both W_O and τ_{INC} are in power law function form

  - L–mode extension =

$$\tau_E^H = \tau_E^L (1 + B^H)$$

where B represents the boundary effect of the H–mode plasma and B^H ~ power law of plasma global parameters

- The approaches taken to study τ_E^H as an extension of τ_E^L

  - A simple model: consider an H–mode plasma as an oversized L–mode plasma and try to express τ_E^H as a function of τ_E^L and the location of truncation

  - ITER confinement database: make use of both the H and L confinement databases. Try fiting τ_E^H data using τ_E^L scaling relation obtained from L–mode database

II. A MODEL FOR ENERGY CONFINEMENT SCALING

- χ^L: a good candidate (as presented in previous APS)

$$\chi^L \propto \underbrace{\frac{nT^{2/3}}{B_p^2} r^3 \left(\frac{1}{T}\frac{\partial T}{\partial r}\right)^2}_{\substack{\Uparrow \\ \text{Local parameters} \\ \text{which determine the} \\ \text{temperature profile shape}}} \bullet \; f \underbrace{\left(R, B_T, a, M, K\right)}_{\substack{\Uparrow \\ \text{Non - local} \\ \text{parameters}}}$$

— Reproducing T_e profiles of both L and H plasmas

— Giving $\tau_E^L \propto n^{0.2}\ I^{0.8}\ P^{-0.6}$, which agrees closely with the scaling $\tau_E^L \propto n^{0.24}\ I^{0.74}\ P^{-0.57}$ given by ITER LDB2 database

— Profile resilience because of L_T^{-2} dependence in χ^L

- It can be shown that, if χ^L is a single term of power law function format, the temperature can be expressed as a product of 4 factors

$$T(Z) = Y_{NC}\, Y_{GP}\, Y_{SZ}\, Y_{PF}(Z) \quad ,$$

Where NC = Numerical constants
GP = Global parameters
SZ = Plasma size factor (Y_{SZ} = 1, for $a_P = a_Z$)
PF = Spatial profile function

- For an L–mode plasma ($a_P = a_Z$):

Assume $T_{(\rho)} = Y_{NC}\, Y_{GP}\, (1-\rho)$,

and $n_{(\rho)} = 3/2\, n_l\, (1-\rho^2)$,

we obtain

$$\tau_E^L = \left(\frac{7}{10}\pi^2 C_\tau\right)\left(\frac{R a_P^2 n_\ell}{P}\right)\left(Y_{NC}\, Y_{GP}\right) \quad .$$

- For an H–mode plasma ($a_P < a_Z$):

  Assume $T_Z = Y_{NC}\, Y_{GP}\, Y_{SZ}\, (1\text{-}Z)$

  and $n(Z) = n_l$

  we obtain

$$\tau_E^H = \left(\frac{2}{3}\pi^2 C_\tau\right)\left(\frac{R a_P^2 n_\ell}{P}\right)\left(Y_{NC}\; Y_{GP}\, \frac{(3-2Z_P)}{Z_P}\right) \quad ,$$

  or

$$\tau_E^H \sim \tau_E^L \left(1+3\,\frac{(1-Z_P)}{Z_P}\right) \quad .$$

  so, for $Z_P = 0.75$, we have $\tau_E^H \sim 2\,\tau_E^L$.

- **The model provides a link between τ_E^H and τ_E^L through the boundary location of the H–mode plasma Z_P**

  – **It shows that, as a consequence of the assumption $\chi^H = \chi^L$, τ_E^H can be fitted with the sum of two power law functions, — τ_E^L and $\tau_E^L B$; that is,**

$$\tau_E^H \sim \tau_E^L (1 + B) \quad ,$$

where τ_E^L is the scaling relation obtained in the L–mode database and B can be assumed as another power law function of plasma global parameters

III. FINDINGS FROM ITER CONFINEMENT DATABASE

- τ_E^L, L–mode confinement scaling
  - τ_E^L scaling can have many different expressions, depending on not only the data selection and meaning but also the numerical fitting procedure, for instance, the log-linear or the power law non-linear
  - Based on ITER LDB2 (SELDB2 = 1), ITER L–mode database, we obtain three τ_E^L scaling relations of comparable fitting errors, namely, the log-linear, the power law non-linear and the model's
- τ_E^L, H–mode confinement scaling (a single term of power law function form):
  - Based on ITERHDB3V5 (Phase ne H), ITER H–mode database
  - For ELMy discharges, the τ_E^H scaling relation can be obtained with the log-linear or the power law non-linear fitting procedures

- $\tau_E^H = \tau_E^L(1+B)$ confinement scaling

  - There exists a convergent solution for the two-term non-linear fitting of H–mode confinement data based on τ_E^L obtained from L–mode database

  - The two-term fitting has a fitting error comparable to the single-term fitting. The ITER τ_E^H prediction (5 s) is also comparable to the single-term, power law, non-linear fitting

  - $(1-Z_P) \sim 0.25$ for all the machines in the database

  - It appears that Z_P scales as

$$\frac{(1-Z_P)}{Z_P} \propto \frac{R^{0.72}\, K^{0.55}\, B^{0.22}\, n^{0.09}}{\varepsilon^{0.74}\, M^{0.22}\, I^{0.11}\, P^{0.10}}$$

Z_P appears affected by ε, R, and K, not so much by other global parameters

IV. SUMMARY

- The H–mode plasma is considered to be an L–mode plasma of larger size truncated at the edge to fit the machines physical size. There is no change in the thermal transport mechanism to go from L to H. In other words, $\chi^H = \chi^L$

- For $\chi^H = \chi^L$, a model is employed to show the connection between τ_E^H and τ_E^L as

$$\tau_E^H = \tau_E^L\left[1 + B\left(Z_p\right)\right] \quad ,$$

Where Z_P is the location of truncation

- Data fitting with ITER confinement database (ITERLDB2 and ITERHDB3V5) has shown that τ_E^H scaling can indeed be made in the function from above. Hence, it appears reasonable to assume $\chi^H = \chi^L$ and the confinement enhancement comes from mainly the changes in the plasma boundary condition

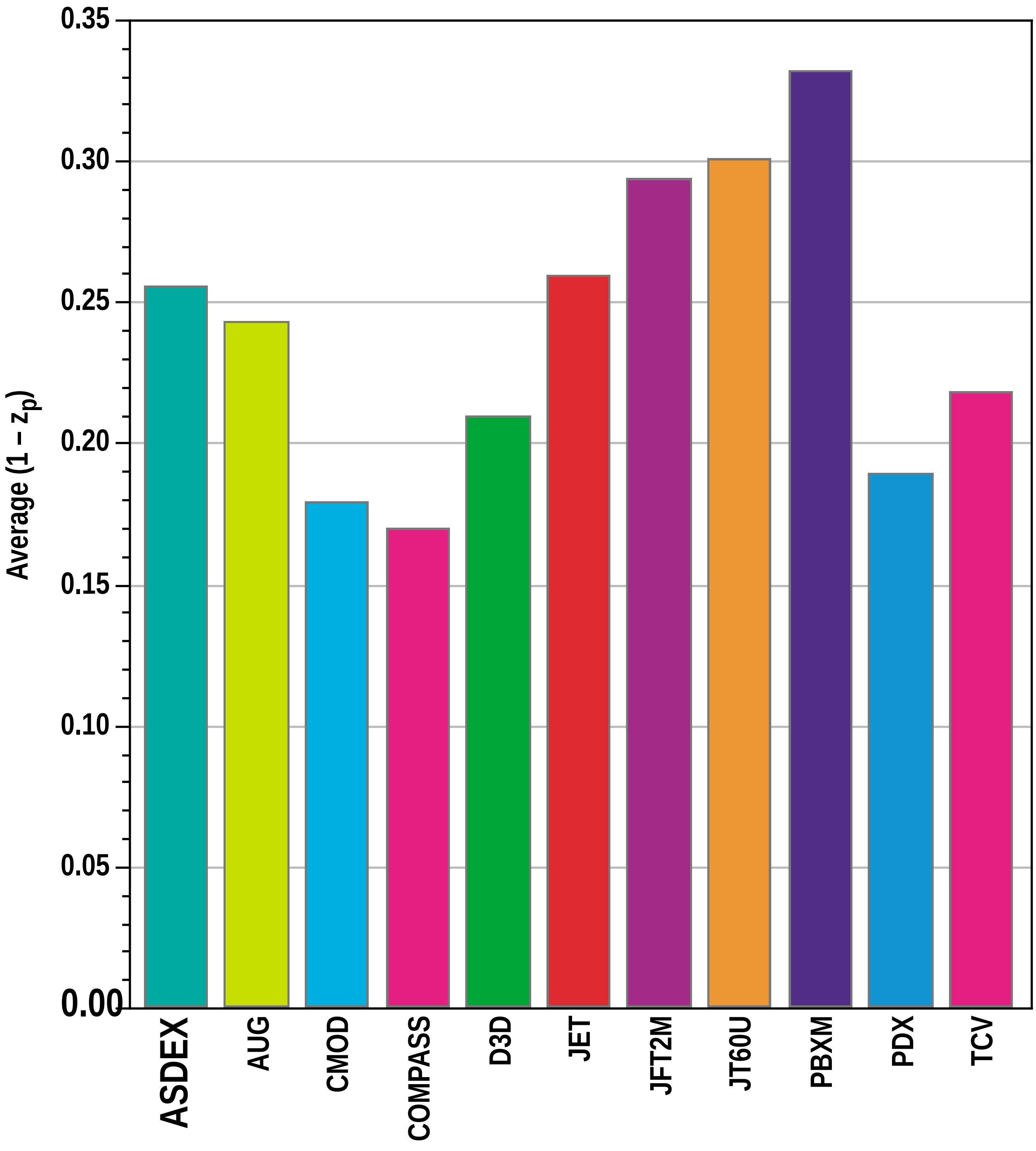
- **$(1-Z_P) \sim 0.25$ for all the machines given in the database. The scaling of Z_P indicates**

$$\frac{1-Z_P}{Z_P} \uparrow \text{ so } \tau_E^H \uparrow \text{ if } R \uparrow,$$

$$\kappa \uparrow,$$

$$\varepsilon = \frac{a}{R} \downarrow.$$

AVERAGE (1 – Z_p) BASED ON τ_E^H GIVEN IN ITERHDB3V5P – ELMY DATABASE



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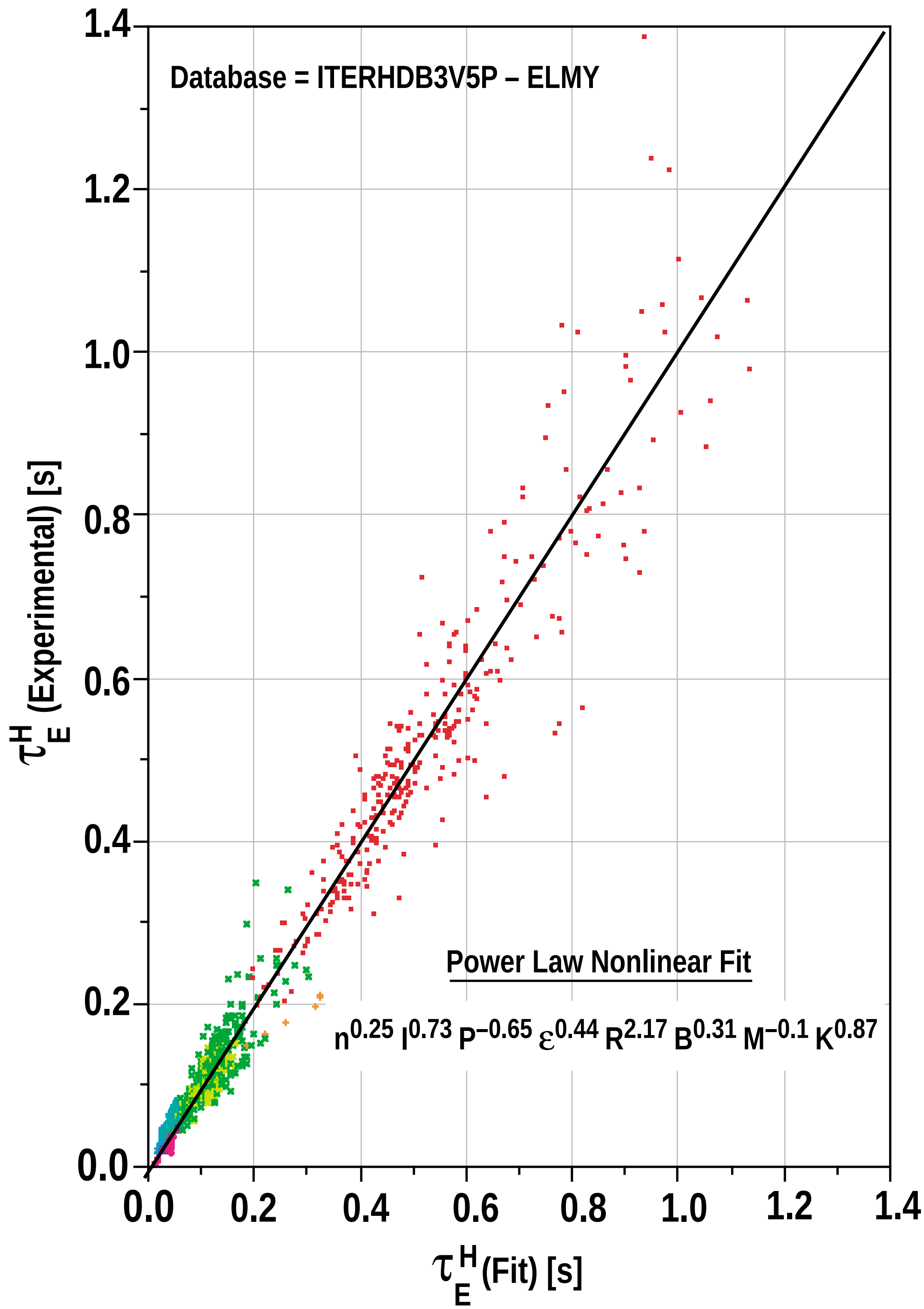
τ_E^H — POWER LAW NONLINEAR FIT TO DATABASE ITERHDB3V5P – ELMY



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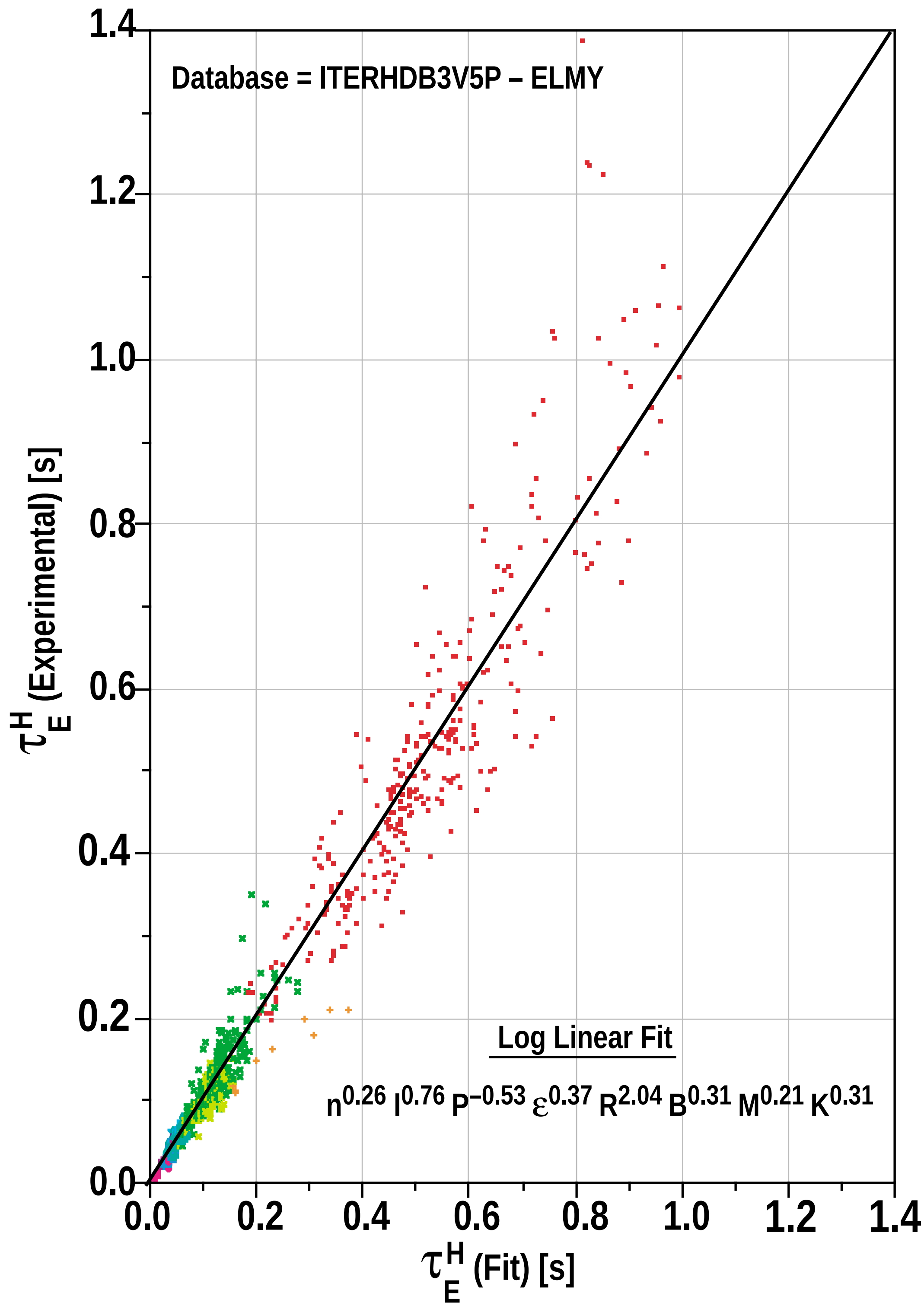
τ_E^H — LOG LINEAR FIT TO DATABASE ITERHDB3V5P – ELMY



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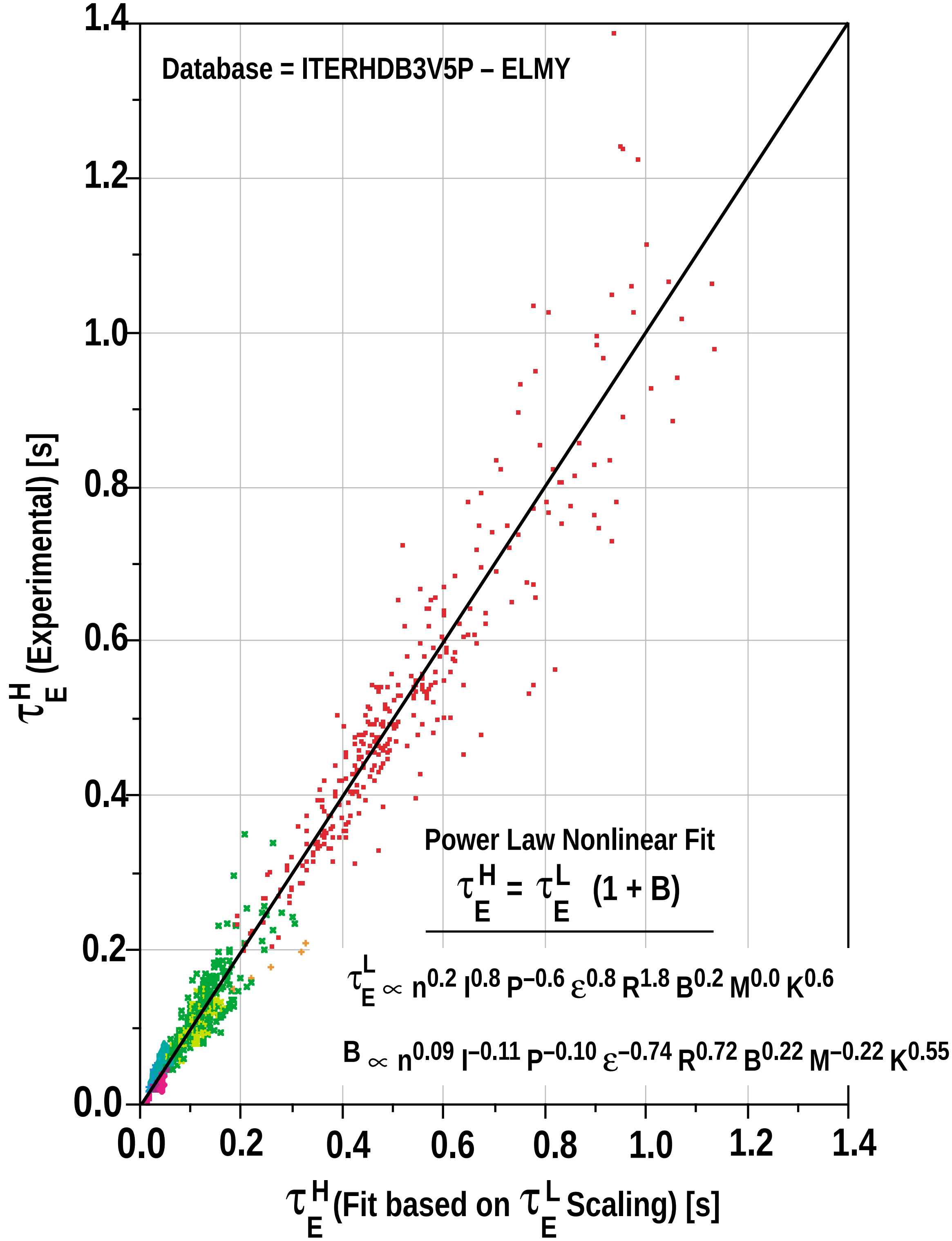
τ_E^H — BASED ON τ_E^L SCALING OF A TRANSPORT MODEL — POWER LAW NONLINEAR FIT TO DATABASE ITERHDB3V5P–ELMY



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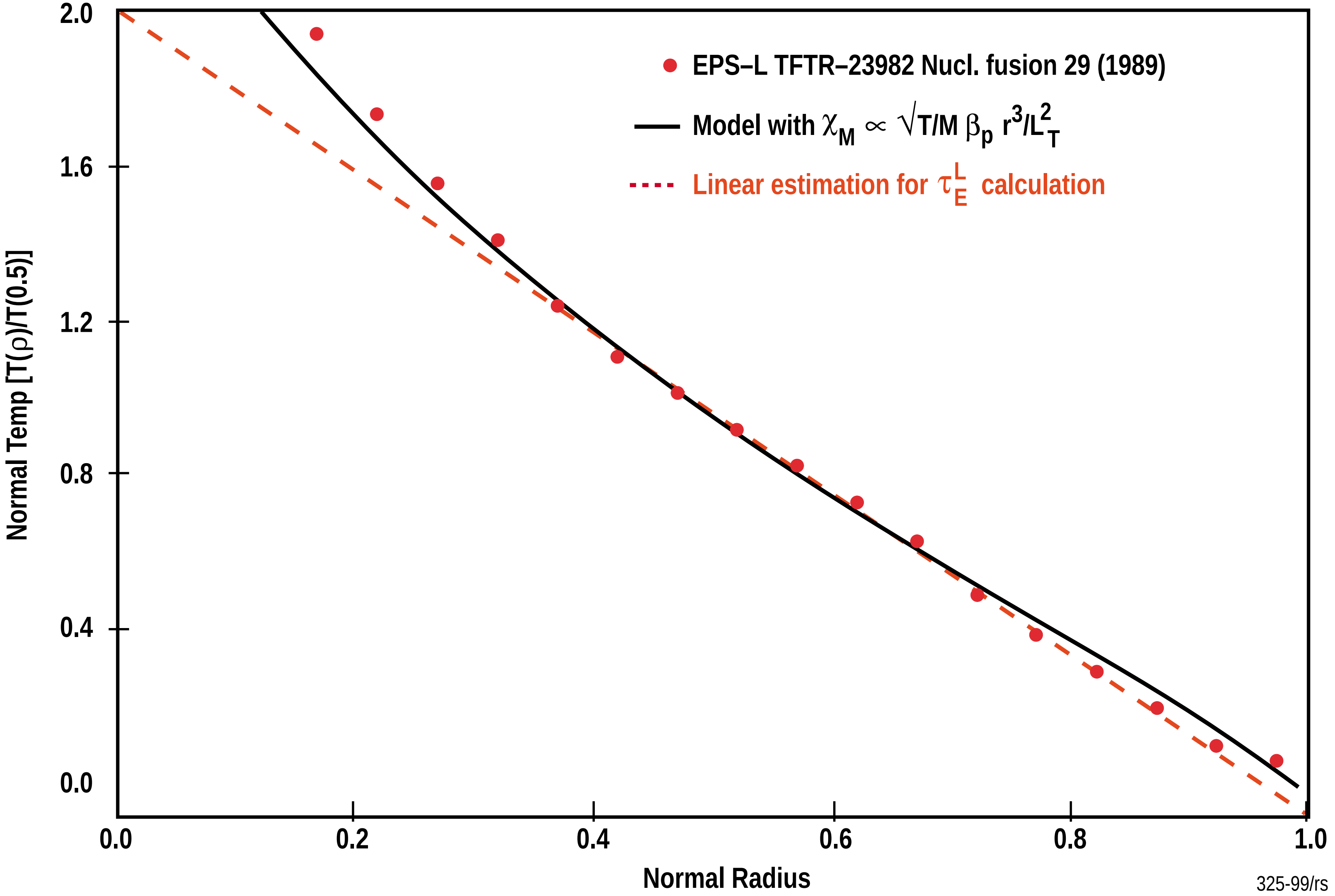
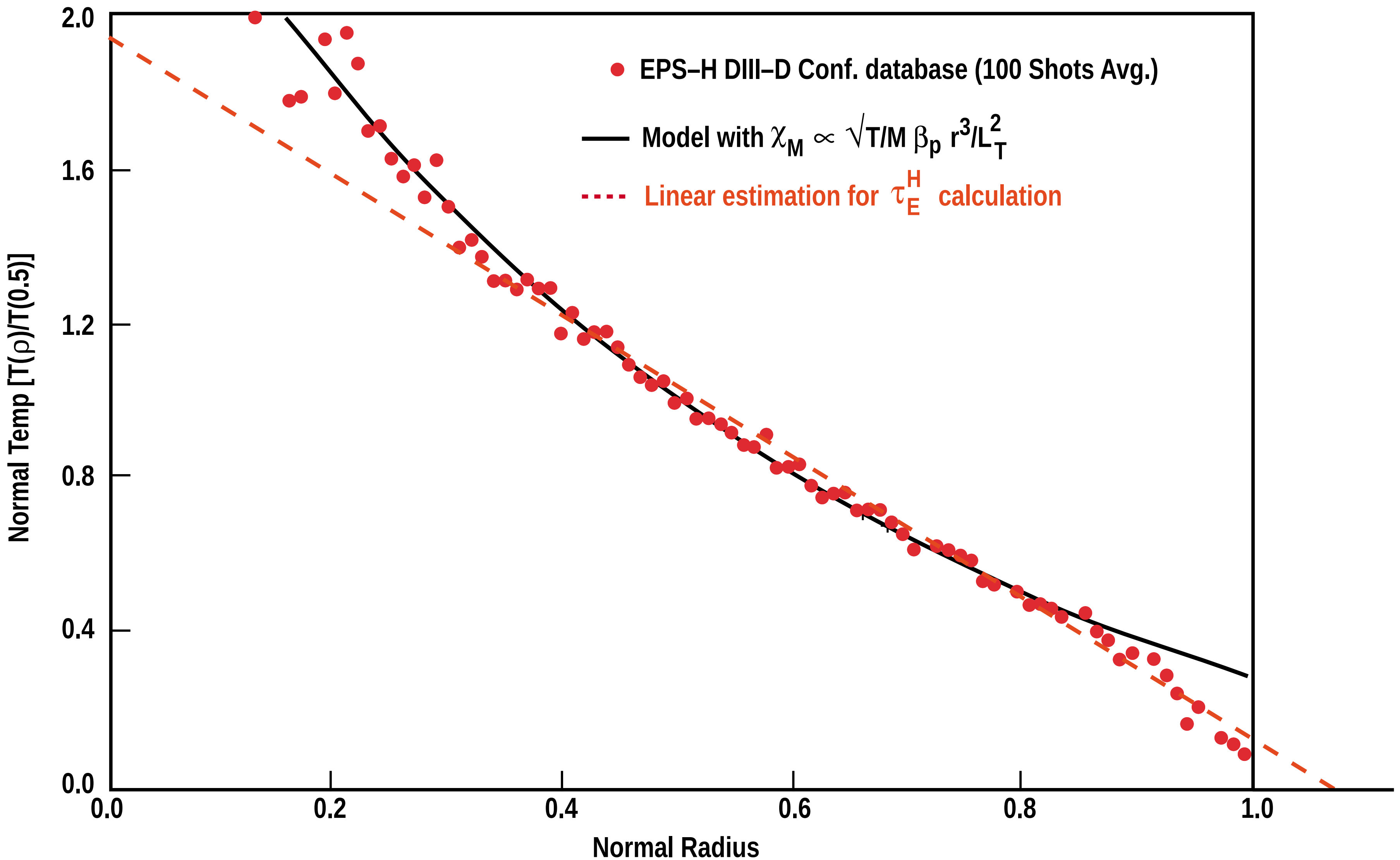
T_e PROFILE SHAPE OF AN L–MODE PLASMA



T_e PROFILE SHAPE OF H–MODE PLASMAS



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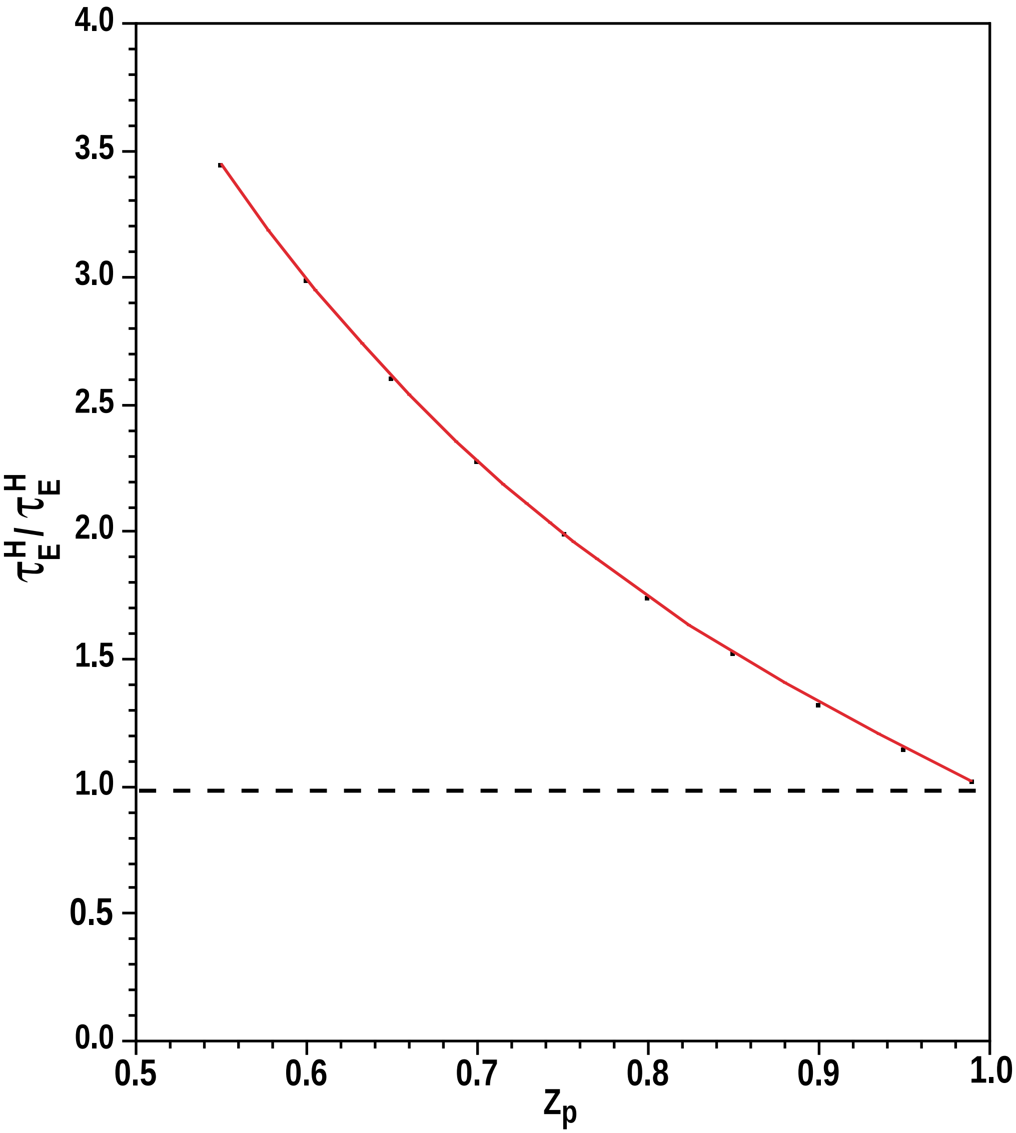
THE CONFINMENT ENHANCEMENT FACTOR τ_E^H / τ_E^H VERSUS Z_p AS DESCRIBED BY THE SCALING MODEL



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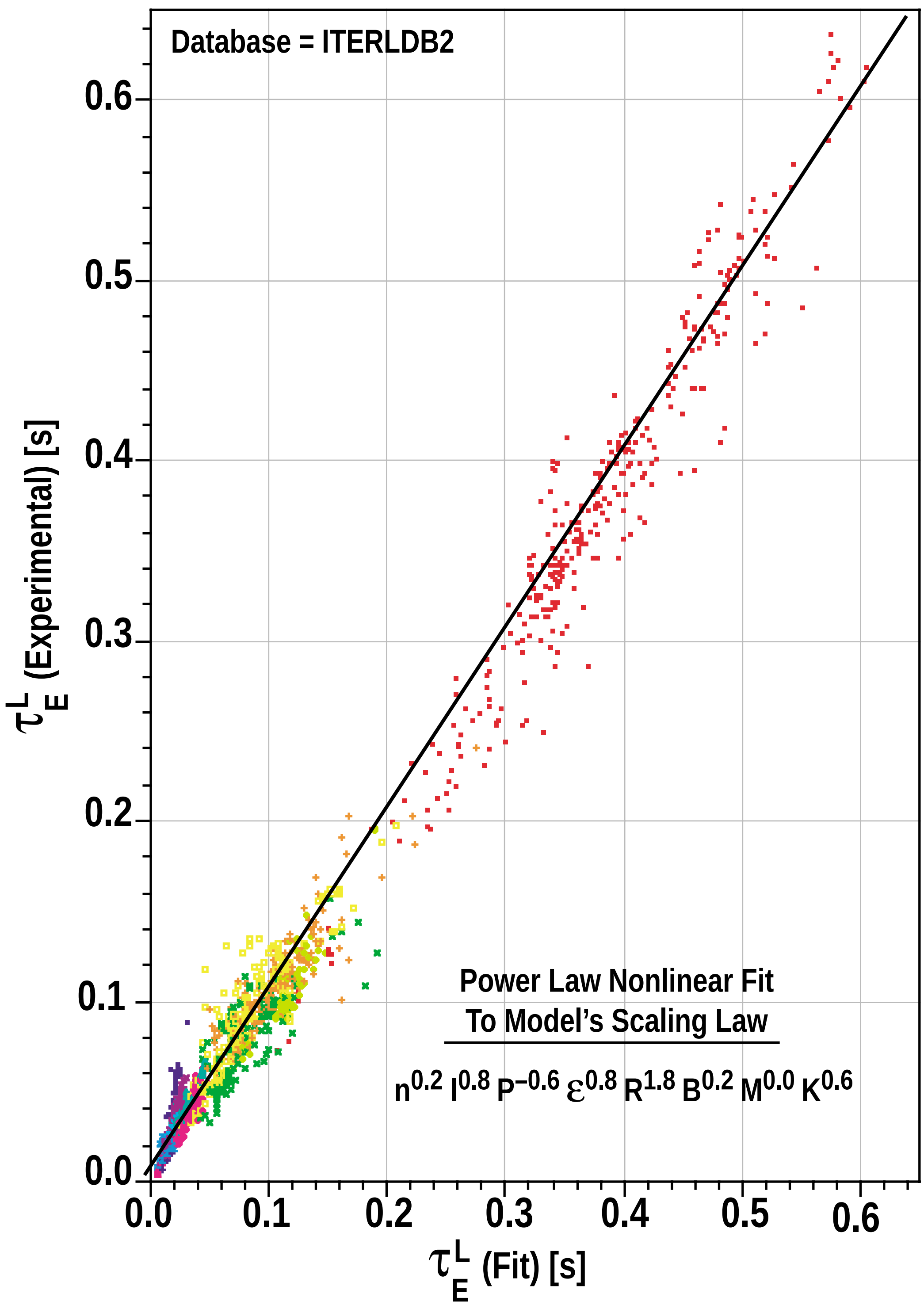
τ_E^L POWER LAW NONLINEAR FIT TO THE MODEL'S SCALING LAW. THERMAL DIFFUSIVITY OF THE MODEL $\chi_M \propto \frac{nT^{3/2}}{B_p^2}\, r^3 \left(\frac{1}{T}\,\frac{\partial T}{\partial r}\right)^2$



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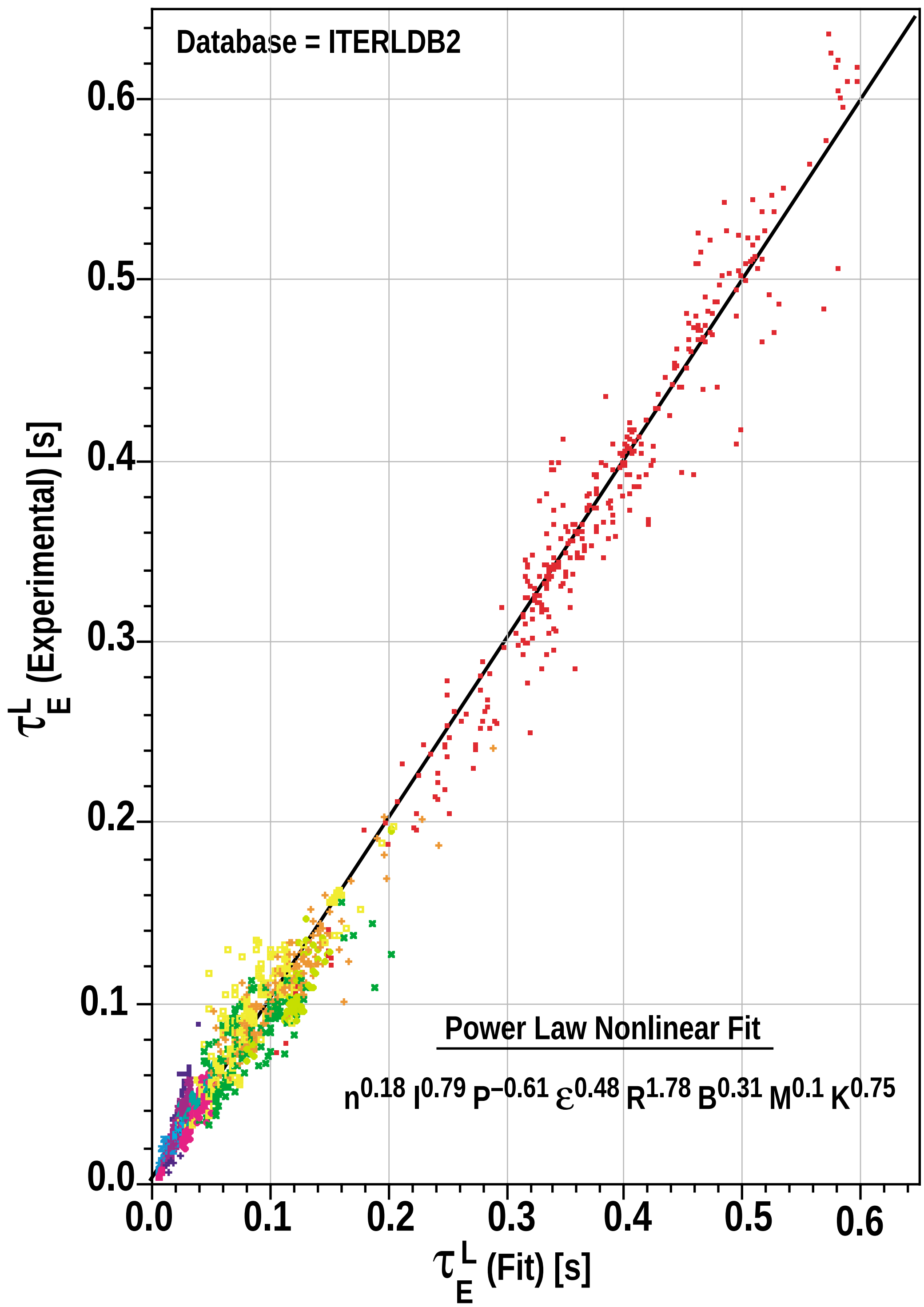
τ_E^L POWER LAW NONLINEAR FIT TO ITERDB2 CONFINMENT DATABASE



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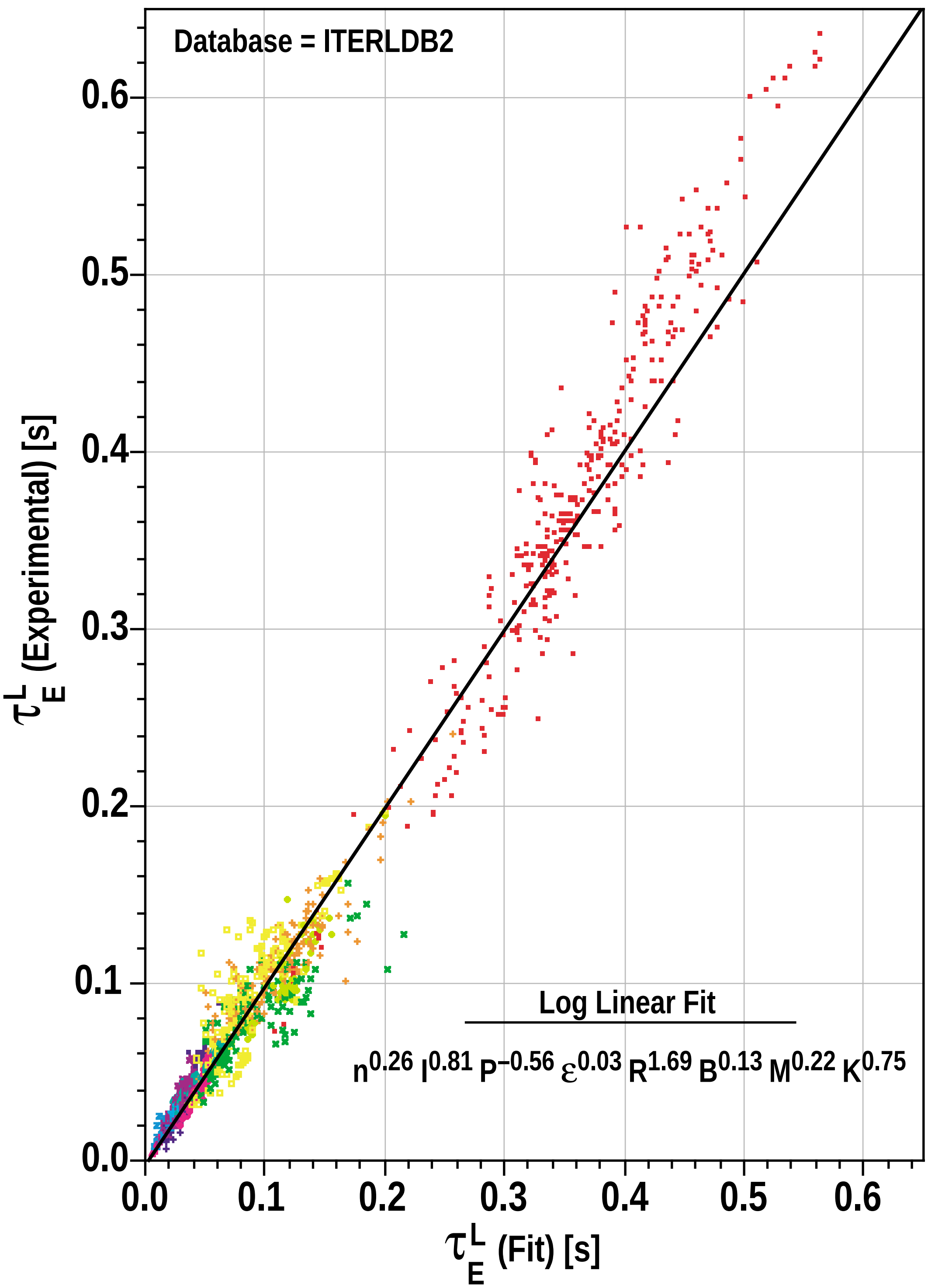
τ_E^L LOG LINEAR FIT TO ITERDB2 CONFINEMENT DATABASE



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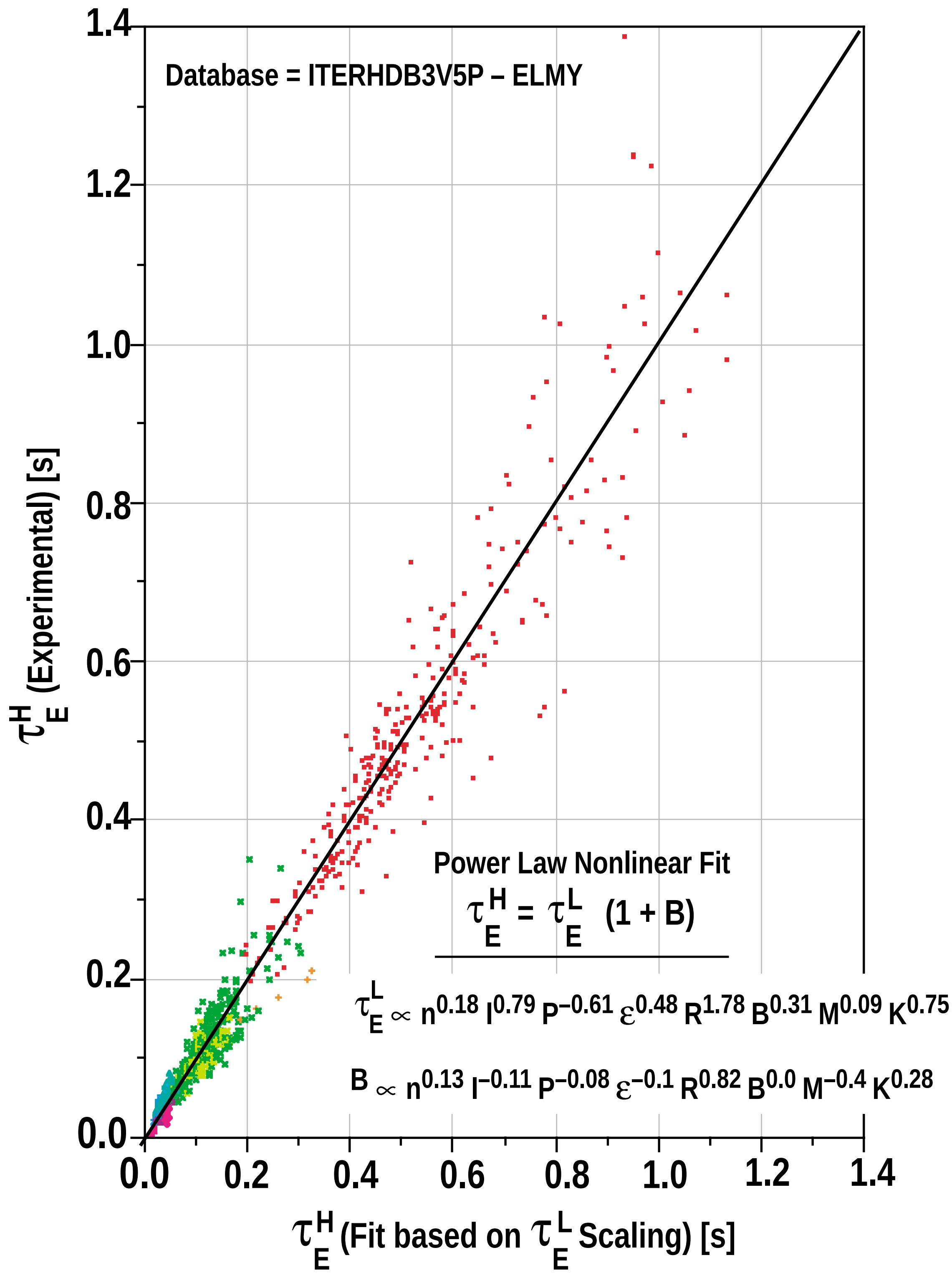
τ_E^H BASED ON τ_E^L SCALING — POWER LAW
NONLINEAR FIT TO DATABASE ITERHDB3V5P – ELMY



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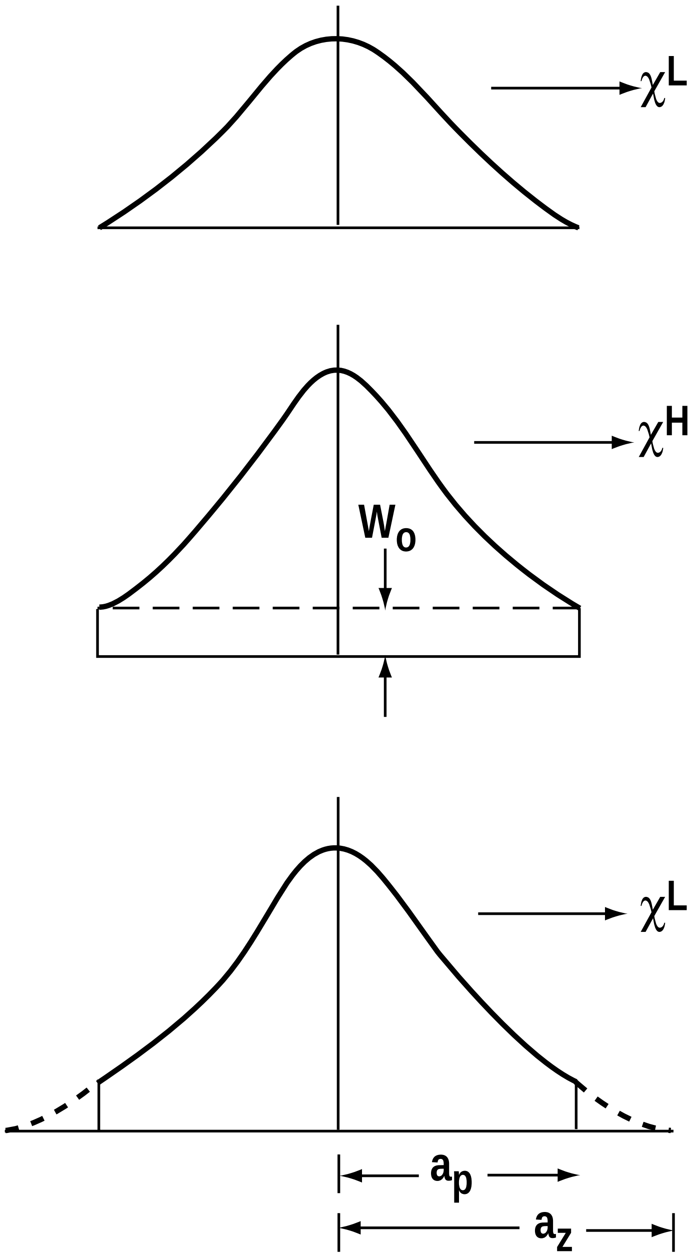
τ_E^H REPRESENTATION WITH DIFFERENT VIEWPOINTS



L–mode

$$\tau_E^L = \prod_i X_i^{Ui}$$

H–mode

$$\tau_E^H = \prod_P X_i^{Vi} \quad \text{(a)}$$

$$\tau_E^H = \frac{W_o}{P} + \tau_{Inc}^H \quad \text{(b)}$$

$$\tau_E^H = \tau_E^L (1 + B) \quad \text{(c)}$$

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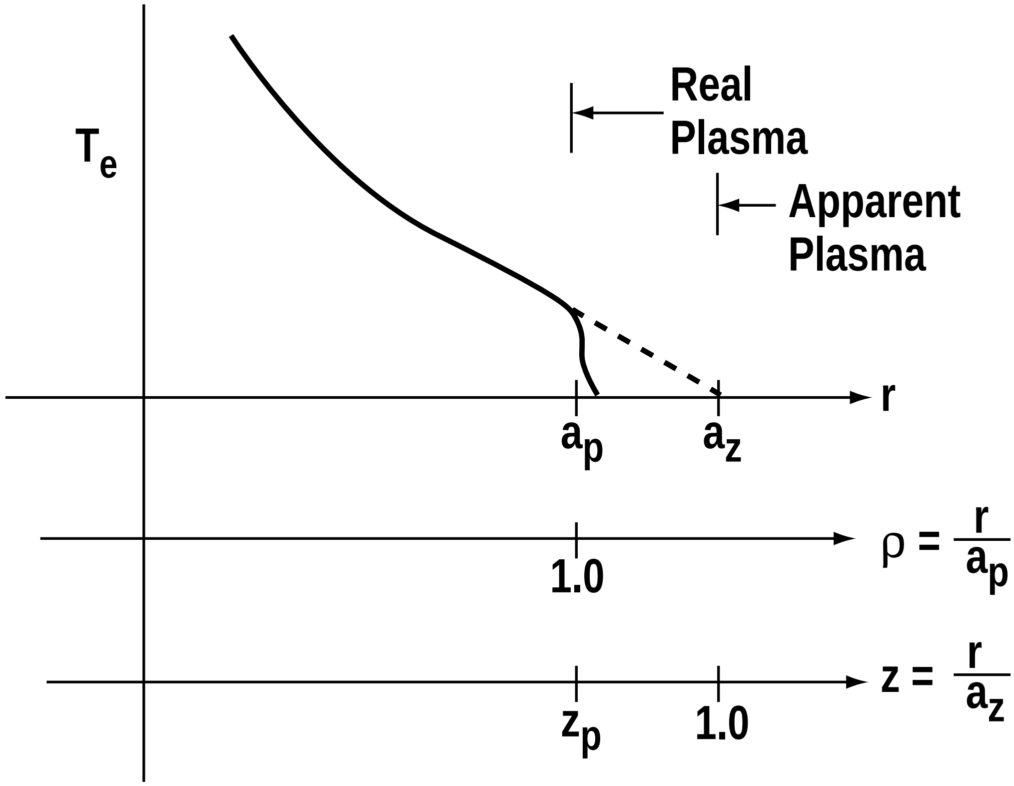
SCHEMATIC OF THE HEAT TRANSPORT MODEL



L–mode: $a_z = a_p$, $\rho = z$

H–mode: $a_z > a_p$, $z_p < 1$

L–mode heat transport model:

$$rn\,\chi^L \left(-\frac{\partial T}{\partial r}\right) = \int_0^r = p(y) \bullet ydy$$

$$\chi^L = C_\chi \frac{nT^{3/2}}{B_p^2} r^3 \left(\frac{1}{T} \frac{\partial T}{\partial r}\right)^2$$

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TABLE_1 (TauE L-mode Fits)

Rows	fit procedure	log-linear	pwr-law nonlin	model nonlin	Remarks
1					
2	SOLUTION				-- L mode TauE
3	C	0.027	0.043	0.067	-- ITERLDB2
4	xn	0.26	0.18	0.2	-- SELDB2 = 1
5	xI	0.81	0.79	0.8	-- 13 Tokamaks
6	xP	-0.56	-0.61	-0.6	-- 1323 slices
7	xeps	0.03	0.48	0.8	
8	xR	1.69	1.78	1.8	Database was
9	xB	0.13	0.31	0.2	prepared by
10	xM	0.22	0.09	0	ITER Confinement
11	xK	0.75	0.75	0.6	Database Group
12					
13	ERRORS				
14	SSE	(39.9) 0.61	0.41	0.46	
15	DFE	(1314) 1322	1314	1322	
16	RMSE	(0.17) 0.021	0.017	0.019	
17	mean TauE	0.144	0.144	0.144	
18					
19	TauE ITER	2.47	2.08	1.95	in secs

LOG-LINEAR $\ln \tau_E^L = \ln C + \sum_i x_i \ln X_i$

PWR-LAW NONLINEAR $\tau_E^L = C \prod_i X_i^{x_i}$

TABLE_II (TauE H-mode Fits)

Rows	fit procedu...	Log-linear	Pwr-nonlin	Col...	TauL EXT_1	TauL EXT_2	TauL EXT_3	Label	Remarks
1				■					
2	SOLUTION			■				SOLUTION	
3				■					
4	Cx	0.051	0.058	■	0.028	0.043	0.067	Cx	
5	xn	0.26	0.25	■	0.26	0.18	0.2	xn	
6	xI	0.76	0.73	■	0.81	0.79	0.8	xI	
7	xP	-0.53	-0.65	■	-0.56	-0.61	-0.6	xP	– H-mode TauE
8	xeps	0.37	0.44	■	0.029	0.48	0.8	xeps	ITERHDB3v5p
9	xR	2.04	2.17	■	1.69	1.78	1.8	xR	ELMY
10	xB	0.31	0.31	■	0.13	0.31	0.2	xB	11 Tokamaks
11	xM	0.21	-0.10	■	0.22	0.09	0.0	xM	1398 slices
12	xK	0.31	0.87	■	0.75	0.75	0.6	xK	
13				■					Database was
14	Cy			■	0.57	0.45	0.2	Cy	prepared by
15	yn			■	-0.03	0.13	0.09	yn	ITER confinement
16	yI			■	-0.22	-0.11	-0.11	yI	database group
17	yP			■	-0.22	-0.08	-0.10	yP	
18	yeps			■	0.94	-0.1	-0.74	yeps	
19	yR			■	1.41	0.82	0.72	yR	
20	yB			■	0.45	0.00	0.22	yB	
21	yM			■	-0.79	-0.40	-0.22	yM	
22	yK			■	0.99	0.28	0.55	yK	
23				■					
24	ERRORS			■				ERRORS	
25	SSE	(31.43)	2.16	■	2.16	2.16	2.17	SSE	
26	DFE	(1389)	1389	■	1389	1389	1389	DFE	
27	RMSE	(0.15)	0.039	■	0.039	0.039	0.040	RMSE	
28	mean TauE		0.173	■	0.173	0.173	0.173	mean TauE	
29				■					
30				■					
31	ITER TauE	7.24	4.94	■	5.48	5.10	5.03	ITER TauE	In Secs
32				■					
33				■					
34				■					

τ_E^L B^H

$$\tau_E^H = \left(C_x \prod_i X_i^{x_i}\right)\left[1 + \left(C_y \prod_j Y_j^{y_j}\right)\right] \qquad \tau_E^H = \tau_E^L\left(1 + B^H\right)$$