GLOBAL ENERGY CONFINEMENT SCALING, UNCERTAINTIES, AND PROJECTIONS TO ITER

presented by

J. C. DeBoo*

General Atomics

*in collaboration with Confinement Database and Modeling Working Group

GENERAL ATOMICS

Confinement Database and Modeling Working Group

Data representatives

Alcator C-mod	J.A. Snipes, M. Greenwald
Asdex/Asdex U	F. Ryter*, M. Alexander, O. Kardaun, A. Kus
Compass-D	M. Valovic
DIII & DIII-D	J.C. DeBoo*, D.P. Schissel, T. Carlstrom
FT-U	G. Bracco
JET	K. Thomsen+, J.G. Cordey*, E. Righi
JFT-2M/JT60-U	Y. Miura*, T. Takizuka*, T. Fukuda, H. Shirai
PBX-M, PDX, TFTR	S.M. Kaye*, D. Mikkelsen
START	M. Walsh
TEXTOR	J. Ongena
Tore-Supra	G.T. Hoang
T10	A. Chudnovskii*, M. Osipenko*
TCV	Y. Martin
Statistical Modelling	O. Kardaun
1-D Modelling	S. Attenberger, D. Boucher*, J. Connor*, W. Dorland, A. Fukuyama, W. Houlberg*, J. Kinsey, M. Kotschenreuther, V. Leonov, D. Mikkelsen, Y. Ogawa*, A. Polevoi, A. Taroni, M. Turner, R.E. Waltz, J. Weiland, G. Bateman

* ITER Expert Group members

- **Global databases: L-mode, H-mode, Threshold**
- **Local database: Profile**

KEY POINTS

- Based on empirical, power law scaling expressions, the thermal energy confinement time in ITER is projected to be ~6 sec.
- A 95% interval estimate of 3.5 - 9 sec is estimated which represents effects such as the use of other functional forms for the scaling expression and the impact of systematic measurement errors.
- Good progress toward physics based scaling has been achieved from nondimensional scaling studies in several tokamaks.
  - validation experiments
  - ρ_*, β and ν_* scaling

H-MODE DATABASE CHARACTERIZATION

- Nearly 6000 time slices from ASDEX, DIII-D, JET, JFT-2M, PBX-M and PDX containing Ohmic, L-mode and H-mode times. New data from additional tokamaks is being added to update the database.

- Set of selection criteria established to choose data of interest to ITER including steady state (small dW/dt) H-mode, NBI heated, limited radiated power and fast ion energy content.

- Have chosen ELM-free and ELMing datasets for regression analysis

  – Log-linear (power law) regressions with the ELM-free dataset meet the high β or Kadomstev constraint (dimensionality check)

  – the ELMy dataset does not, perhaps due to mixing discharges with various types of ELMs

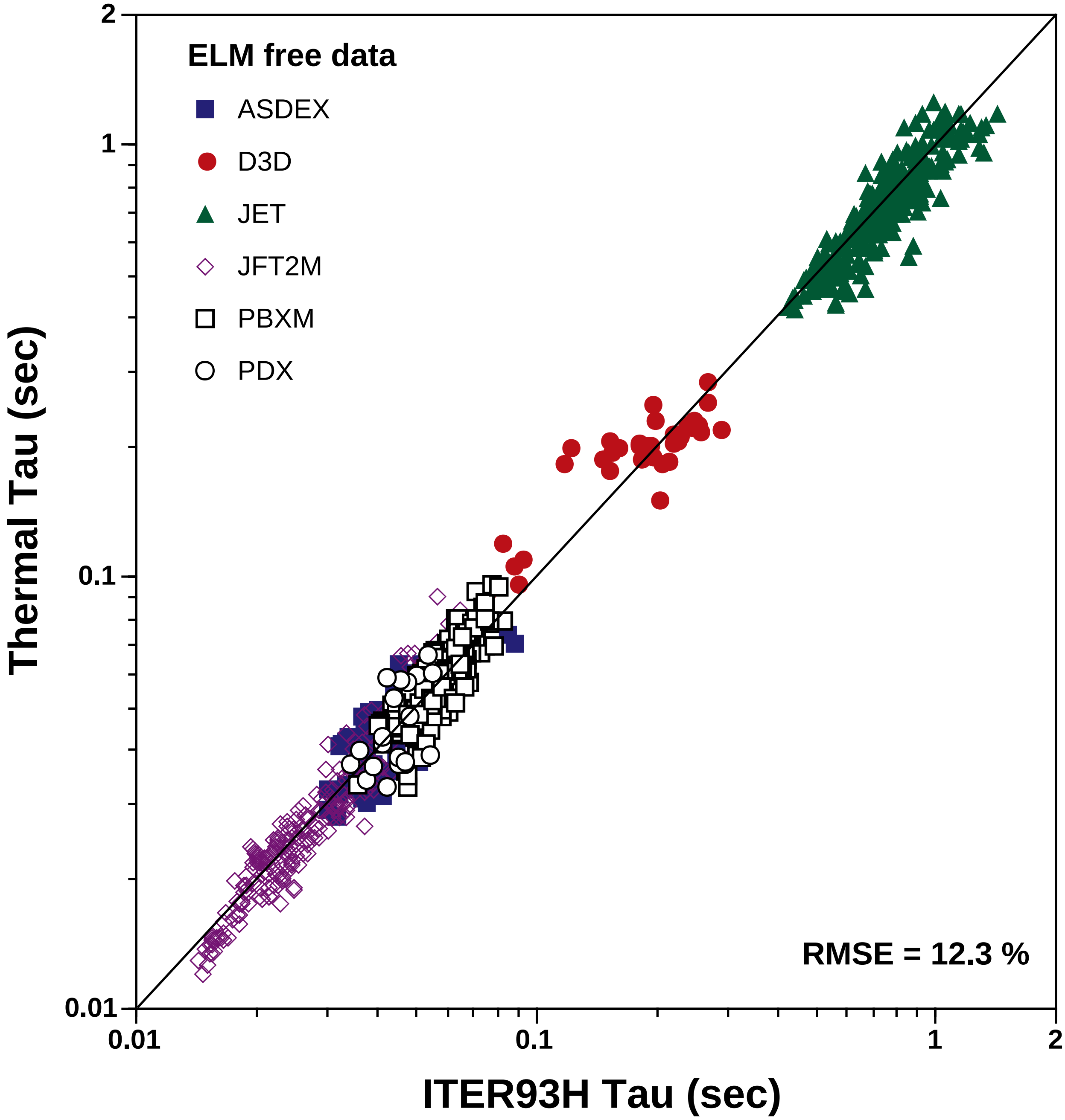
  – working on including ELM characterization

- Log-linear regression on ELM-free dataset yields

ITER93H

$$\tau_{th} = 0.036\ I^{1.06} B^{0.32} P^{-0.67} n_e^{0.17} M^{0.41} R^{1.79} \varepsilon^{-0.11} \kappa^{0.66}$$

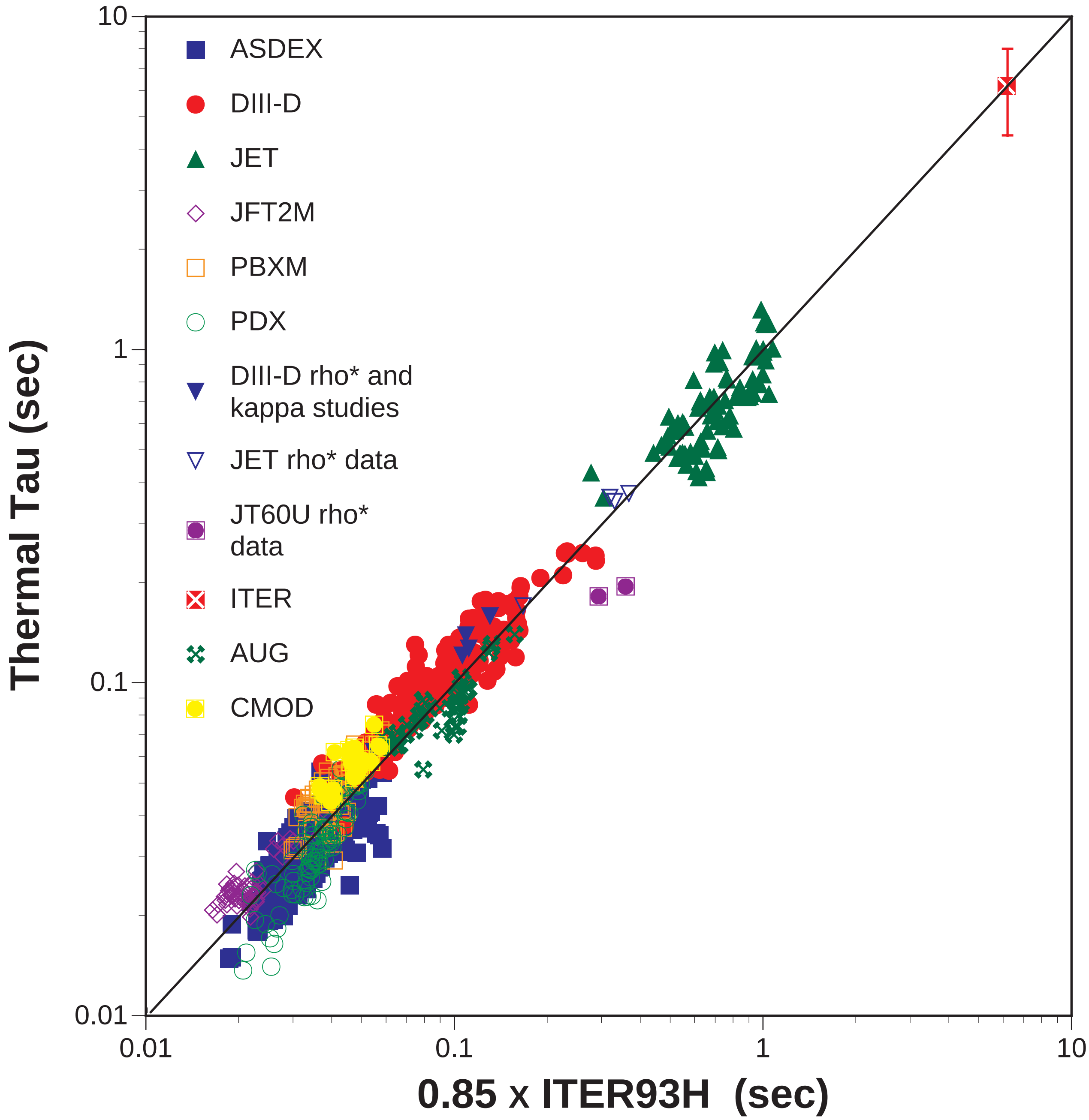
H-MODE SCALING
REGRESSION with ELM-free DATA



$$0.036\ I_p^{1.06}\ B_T^{0.32}\ P_L^{-0.67}\ n_e^{0.17}\ M^{0.41}\ R^{1.79}\ e^{-0.11}\ k^{0.66}$$

GENERAL ATOMICS

ITER93H SCALING
COMPARED TO ELMy DATA



J.C. DeBoo 10/22/96

GENERAL ATOMICS

NONLINEAR FUNCTIONAL FORMS

- The most recent nonlinear functional form developed by Dorland and Kotchenreuther has one fewer fitting parameter than ITER93H

  DK96

  $$\tau_{th} = 0.069\ I^{0.94} B^{0.41} P^{-0.69} M^{0.28} R^{1.57} \kappa^{0.43} g_2{}^{0.33 \ln q_{eng}}$$

  where $g_2 = (\frac{q_{95}}{q_{eng}}) a \sqrt{n\varepsilon}$ **and** $q_{eng} = \frac{5a^2 B\kappa}{IR}$

  – RMSE = 11.4 %, somewhat smaller than ITER93H

  – two weakest principal components less uncertain compared to ITER93H and smaller extrapolation to ITER

- Offset-linear functional forms have also been proposed

  $$W_{th} = W_0 + \tau_0 P$$

  where $W_0 = C_1\ I^{x_I} B^{x_B} n^{x_n} M^{x_M} R^{x_R} \kappa^{x_\kappa} a^{x_a}$

  and $\tau_0 = C_2\ I^{z_I} B^{z_B} n^{z_n} M^{z_M} R^{z_R} \kappa^{z_\kappa} a^{z_a}$

  – because there are too few tokamaks with different sizes to determine all the geometric exponents in this functional form additional assumptions must be made

  – projections to ITER are more optimistic than ITER93H

PHYSICS-BASED SCALING STUDIES

- **Dimensionless parameter scaling, DPS**

  Global $\Omega\tau = F(\rho_*, \beta, \upsilon_*, q, ...)$

  Local $\frac{\chi}{Ba^2} = G(\rho_*, \beta, \upsilon_*, q, ...)$

  – $\lambda_D << \rho_i$

  – atomic physics is negligible in confinement and transport

- **Validation of technique**

  – match all dimensionless parameters in two different tokamaks with different engineering variables

  – should obtain same value of normalized confinement time, $B\tau$, and normalized thermal diffusivity

- **Similarly, if assume ρ_* scaling of F or G is separable then can study ρ_* scaling**

$$\tau = \tau_B \rho_*^{-\alpha} F(\beta, \upsilon_*, q, ...)$$

or $$\chi = \chi_B \rho_*^{\alpha} G(\beta, \upsilon_*, q, ...)$$

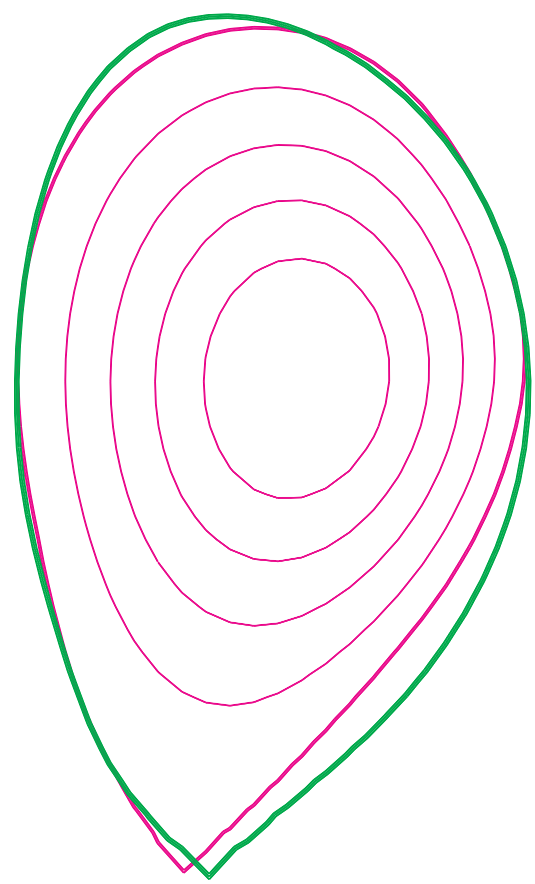
where $\alpha = 1 \Rightarrow$ gyro-Bohm scaling

$\alpha = 0 \Rightarrow$ Bohm scaling

ELMing H-mode Discharges with Identical Dimensionless Parameters Have Been Developed on DIII-D and JET

DIII-D plasma shape closely matched that of JET

Parameter	DIII-D	JET
a (m)	0.56	0.97
B (T)	2.10	1.07
I_p (MA)	1.14	1.0
n ($10^{19}m^{-3}$)	7.6	2.4
W_{th} (MJ)	0.60	0.84
P_{tot} (MW)	6.1	4.25
τ_{th} (s)	0.10	0.20
$B\tau_{th}$	0.21	0.21



The normalized thermal confinement times for DIII-D and JET are equal for these H-mode identity plasmas

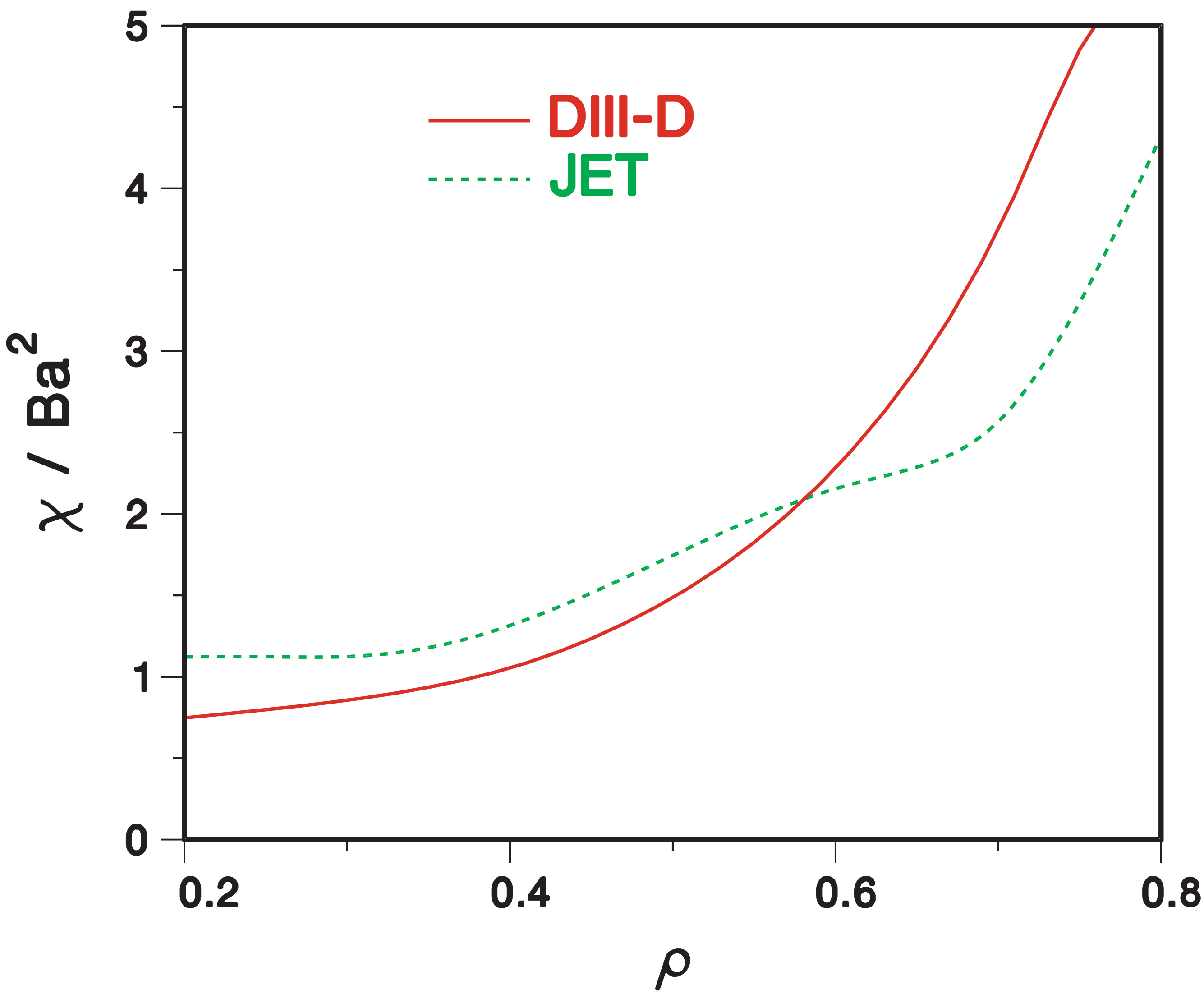
J. G. Cordey, B. Balet

JET

T. C. Luce, C. C. Petty

GENERAL ATOMICS

The agreement between the DIII-D and JET one-fluid diffusivities indicates that dimensionally identical discharges have the same local transport



JET

GENERAL ATOMICS

SCALING WITH DIMENSIONLESS PARAMETERS

- ρ_* scaling experiments in ITER-like discharges have been performed on ASDEXU, DIII-D, JET and JT-60U. For low q, ELMing H-mode discharges, gyro-Bohm-like scaling was found.

- Recent DIII-D and JET dimensionless parameter scaling experiments in H-mode agree on the β and ν_* scaling

  – $\tau \propto \beta^0 \upsilon_*^{-1/3}$

- DPS results essentially agree with ITER93H scaling for ρ_* and ν_* scaling but disagree with β scaling

  ITER93H : $\tau \propto \tau_B \rho_*^{-0.74} \beta^{-1.23} \upsilon_*^{-0.28}$

  DPS : $\tau \propto \tau_B \rho_*^{-1} \beta^0 \upsilon_*^{-1/3}$

- Disagreement in β scaling is outside range of uncertainty in each expression. Reasons for disagreement are not yet understood but are under investigation.

- When proposed DPS experiments to determine q scaling are completed, a complete local transport scaling model will be available.

NONLINEAR COMPARED TO LOG-LINEAR FUNCTIONAL FORMS

- Compare DK96 to ITER93H

$$\tau_{DK96} = 0.069\ I^{0.94} B^{0.41} P^{-0.69} M^{0.28} R^{1.57} \kappa^{0.43} g_2{}^{0.33 \ln q_{eng}}$$

note $g_2 \ \alpha \ \dfrac{\sqrt{\beta\varepsilon}}{\rho_*}$

then $\dfrac{\tau_{DK96}}{\tau_{93H}} \ \alpha \ F \ \alpha \ \rho_*^{\,0.39-0.33 \ln q_{eng}}$

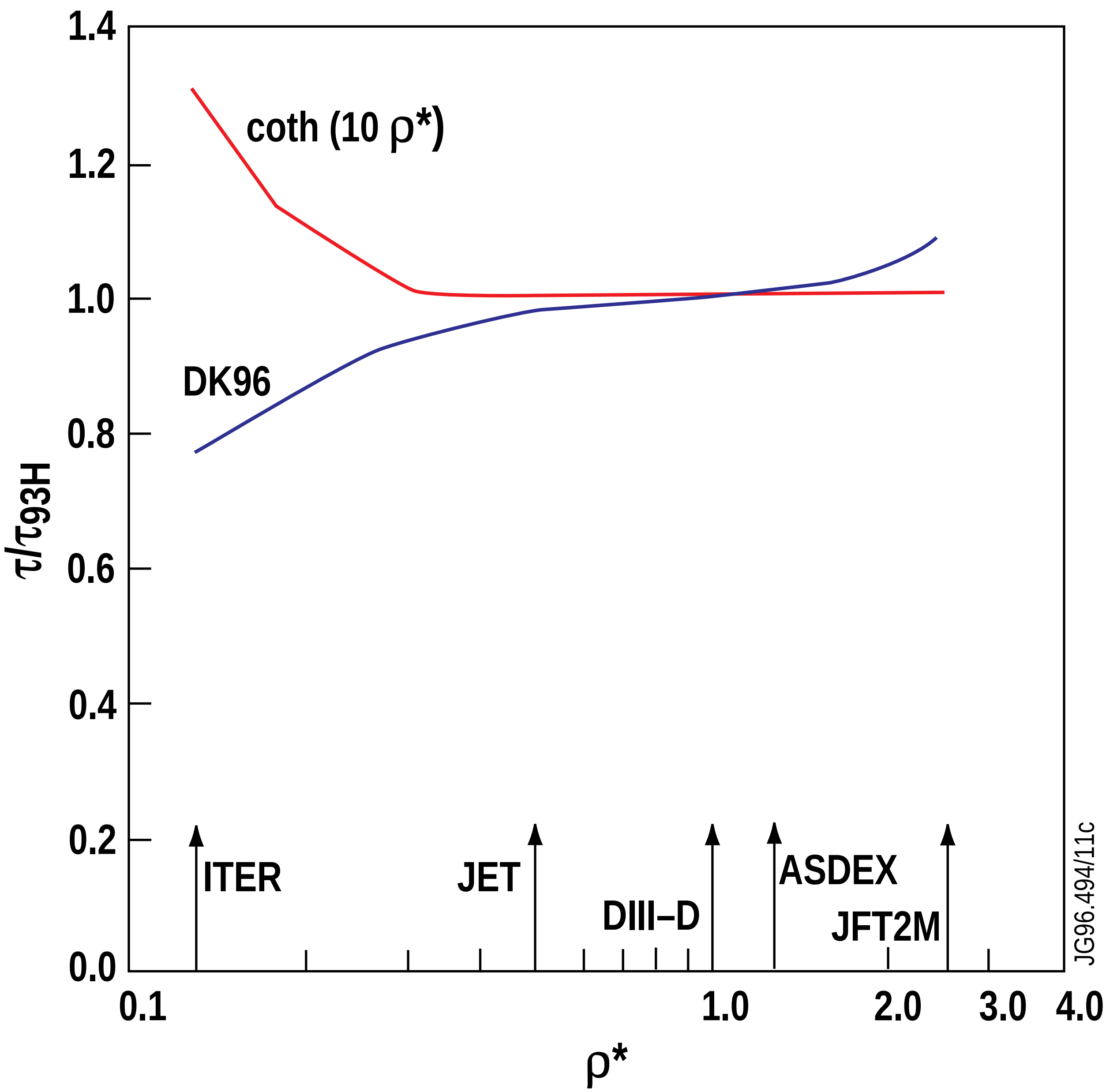
- F ~ 1 over range in dataset, but drops to ~0.7 for ITER
  - – need compelling physics reason to motivate this strong curvature produced outside the range of the database

- Other nonlinear functional forms can be formed with values near 1 over the range in the database. One with this property but which increases for ITER is

$$\frac{\tau_{JC}}{\tau_{93H}} = \coth(\pi q_{eng} \rho_*)$$

- Functional forms $\tau = F^{\pm\alpha}\ \tau_{93H}$ with the above property of F have an unbounded range of predictions for ITER.

Two Nonlinear Functions which Agree well with the Database and Dramatically Differ in their ITER Prediction



J.G. CORDEY

JET

GENERAL ATOMICS

ADDITIONAL COMMENTS AND CONCERNS

- ITER93H
  - the two weakest principal components are relatively more uncertain, smaller variation within the database, yet require a large step size to ITER of several standard deviations.
- ITER operation is up to ~1.4 x n_{GW} but the ELM-free dataset has a mean value of 0.45 x n_{GW}
  - recent ASDEXU and DIII-D pellet injection experiments show no degradation in confinement up to 1.5 x n_{GW}
- ITER will operate just above the H-mode power threshold but the database discharges are generally well above the threshold.
  - operation in C-Mod near the threshold shows no degradation in confinement

SUMMARY OF ITER PROJECTIONS

Log-linear Expressions

- 0.85 x ITER93H

  – ITER projection: τ_{th} = 6.2 ± 1.8 sec

  – 95% confidence interval

$$\frac{\delta\tau}{\tau} = \frac{2\sigma}{\sqrt{N_{eff}}}\left(1 + \sum_{j=1}^{n} \frac{\lambda^2_{ITERj}}{\lambda^2_{pcj}}\right)^{1/2} = 29\% \qquad N_{eff} \sim N/4$$

- Other log-linear regressions on both ELMy and ELM-free datasets also result in ITER projections near or above 6 sec

Nonlinear Expressions

- 0.85 x DK96

  – ITER projection: τ_{th} = 4.3 ± 1 sec (2σ)

- Offset-linear scaling expressions typically give more optimistic ITER projections, τ ~ 9 sec (OL95, Kardaun), but require additional assumptions on size dependence and therefore are more uncertain.

ITER PROJECTIONS (CONT.)

Dimensionless Parameter Scaling

- Assuming ITER operation in ELMing H-mode can be obtained along a gyro-Bohm scaling path
- $B\tau \propto \rho_*^{-\alpha}$ where α=3.0 for gyro-Bohm and α=2.7 for ITER93H
- ITER demonstration discharges in JET and DIII-D

Tok	β_N	ρ_*/ρ_{*ITER}	α	τ_{ITER}
JET	2.2	5.51	2.7	6.4 sec
			3.0	10.5
DIII-D	2.0	7.32	2.7	11.8
			3.0	21.0

- Projections are optimistic compared to ITER93H
- Detailed error analysis is required to estimate uncertainty in projections

UNCERTAINTY IN ITER PROJECTIONS

- Taking into account both statistical and physics considerations, most members of the database working group believe the ITER93H scaling expression is the best choice of the various possible functional forms considered.

- However, the uncertainty in the ITER projection should consider

  - projections based on the various functional forms with similar statistical significance

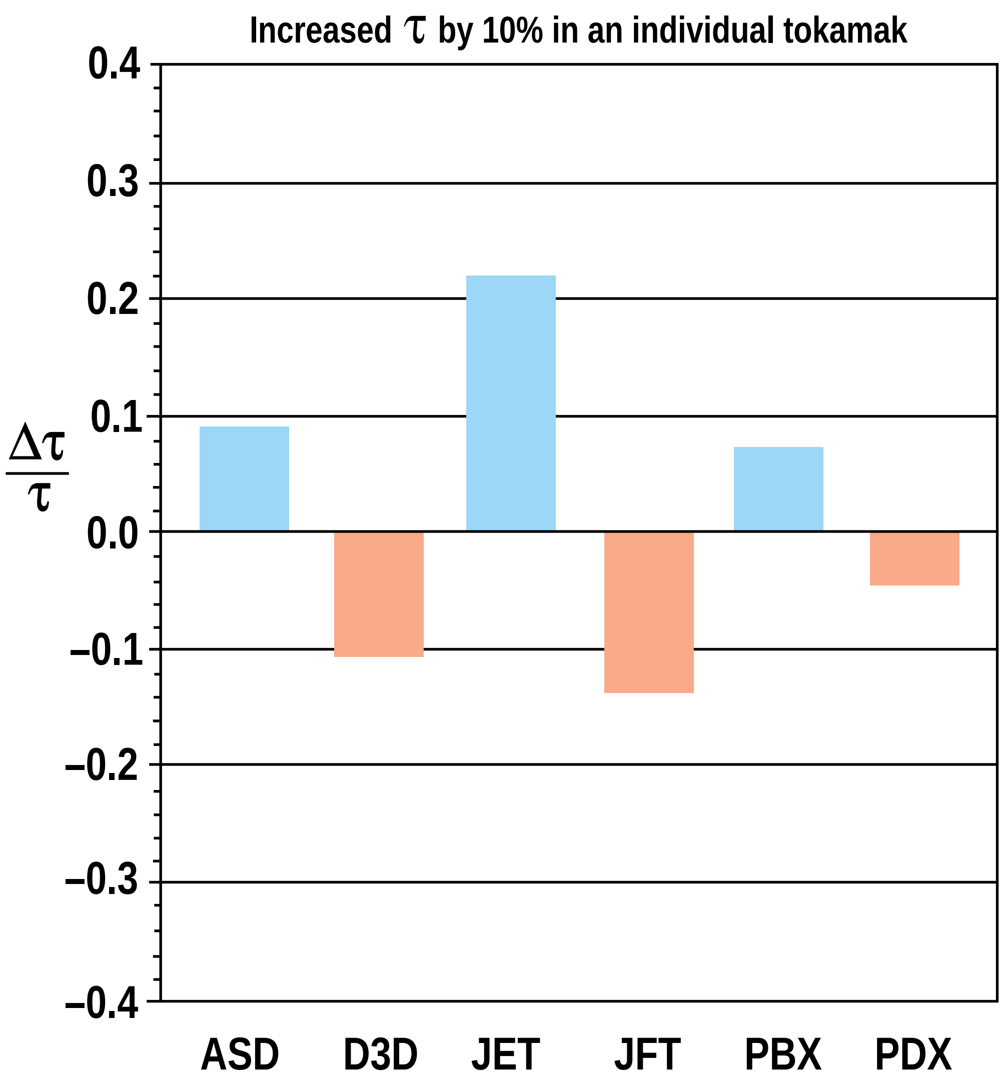
  - other effects such as systematic, tokamak to tokamak, measurement errors

- One can define a 95% interval estimate as one which contains all ITER projections from statistically comparable fits.

- By considering the distribution of ITER projections obtained by employing various functional forms and estimating systematic errors, an uncertainty interval of 3.5 - 9 sec was estimated.

Sensitivity of ITER93H Predictions to Systematic Errors

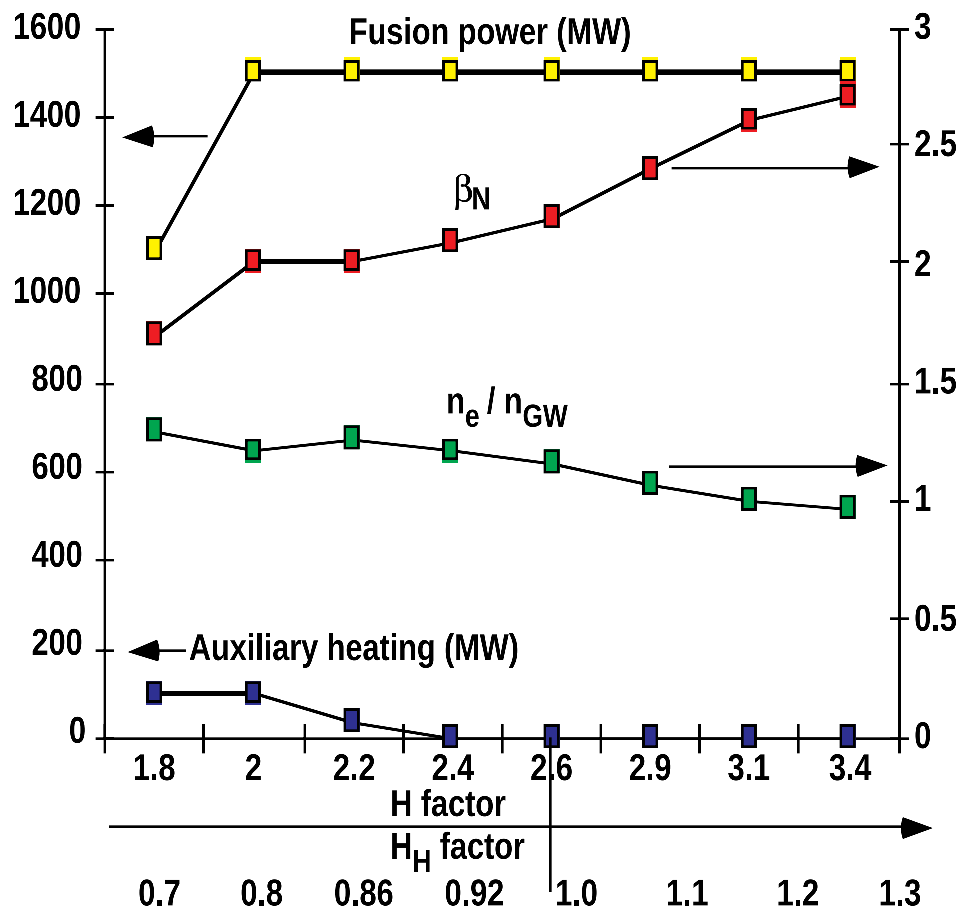
- 10% Systematic errors can produce 15% to 20% variations in ITER predictions



O.J. KARDAUN

Asdex

ITER PERFORMANCE vs. CONFINEMENT ENHANCEMENT FACTOR (H_H) WITH DIVERTOR IMPURITY MODEL



GENERAL ATOMICS

CONCLUSIONS AND FUTURE WORK

- The database and modeling working group has recommended using the ITER93H scaling expression for addressing ITER issues where information on parametric scaling of global confinement time is required.
- Several log-linear scaling expressions project to τ_{th} ~ 6 sec $\pm$ 30% for ITER. However, in recognition of a wider span of projections from non-linear functional forms, the group has recently recommended ITER consider contingency scenarios based on a confinement time interval of 3.5 - 9 sec.
- Future H-mode database work
  - new regression analysis on combined dataset with new data from ASDEXU, C-Mod, DIII-D, JET and JT-60U
  - ELM characterization
  - add results from new dimensionless parameter scaling experiments to database
  - further study on β scaling discrepancy