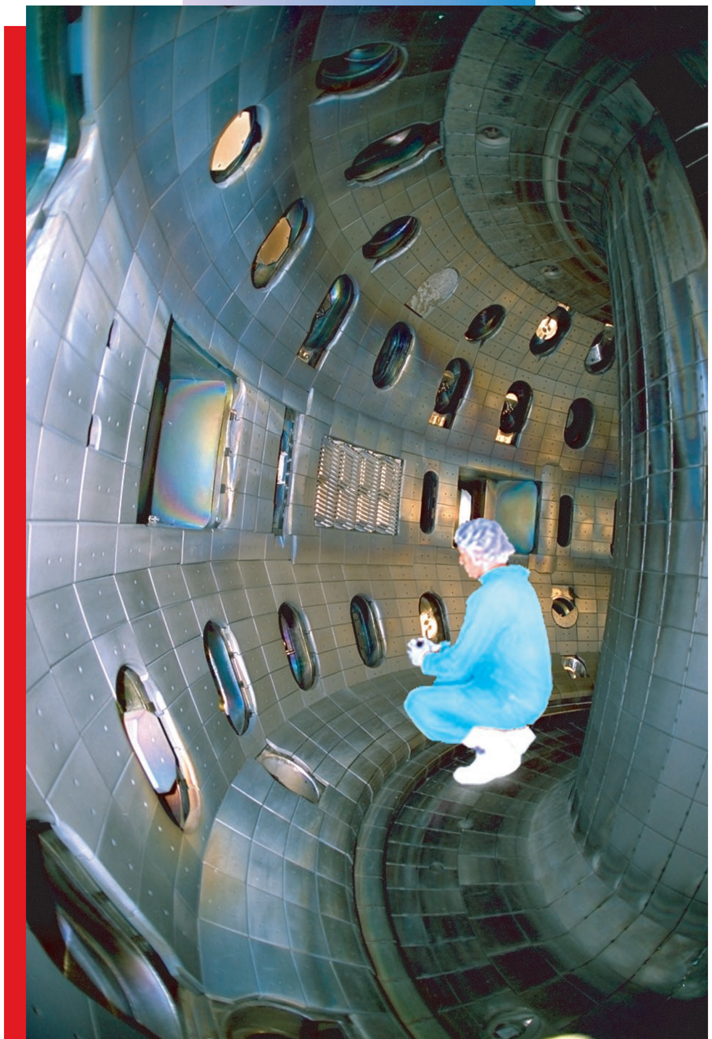


A THEORETICAL AND EXPERIMENTAL INVESTIGATION INTO ENERGY TRANSPORT IN HIGH TEMPERATURE TOKAMAK PLASMAS

Presented by

D.P. SCHISSEL

Presented to

APS Centennial Meeting

March 20–26, 1999
Atlanta, Georgia

058–99

GENERAL ATOMICS

KEY POINTS

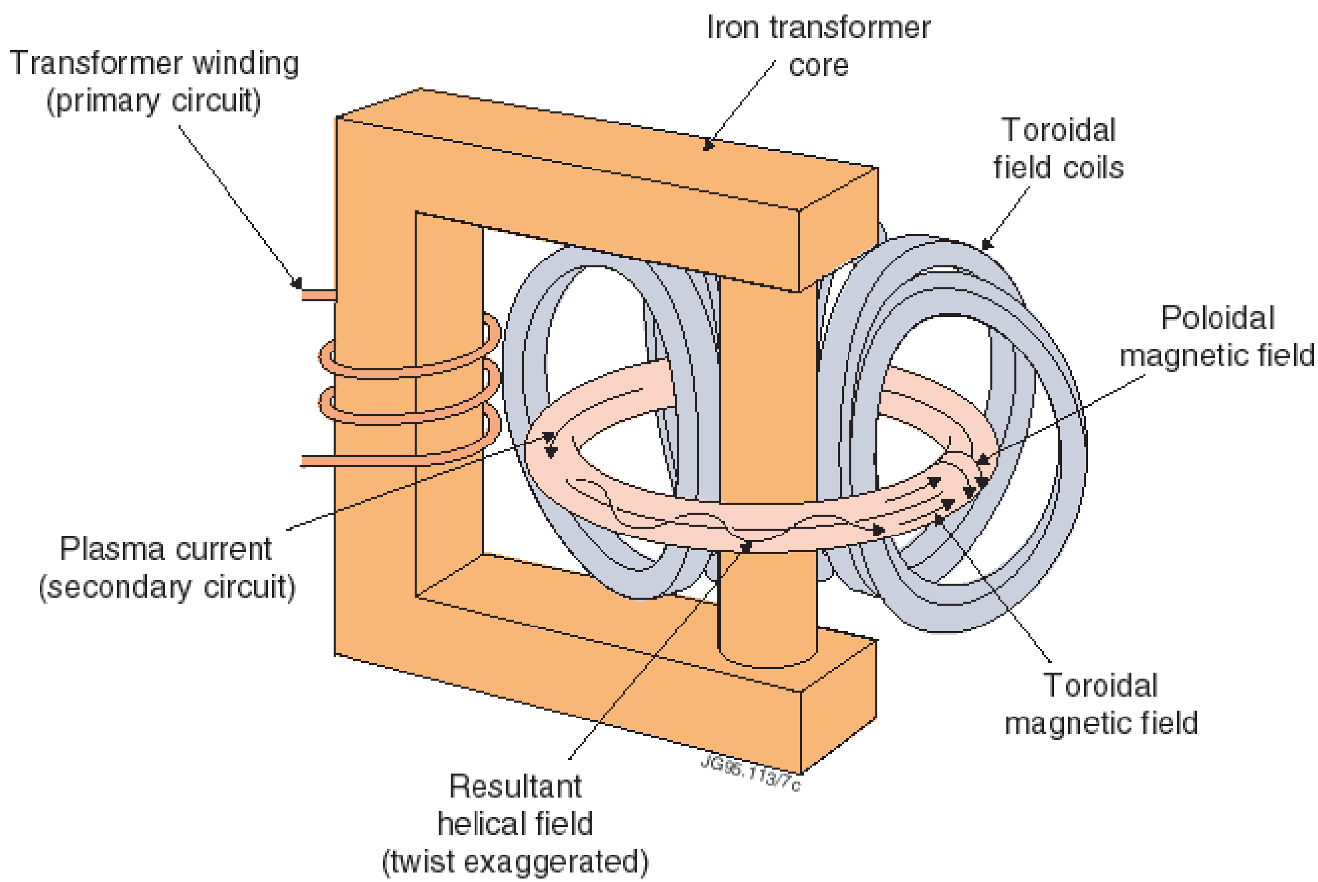
- *Considerable progress has been made in the understanding of the transport processes taking place in a tokamak*

- *In the theoretical area large codes have been developed which simulate the turbulence and ensuing radial transport*
  - *Fully validating one-dimensional model describing transport throughout the radial region is not available*

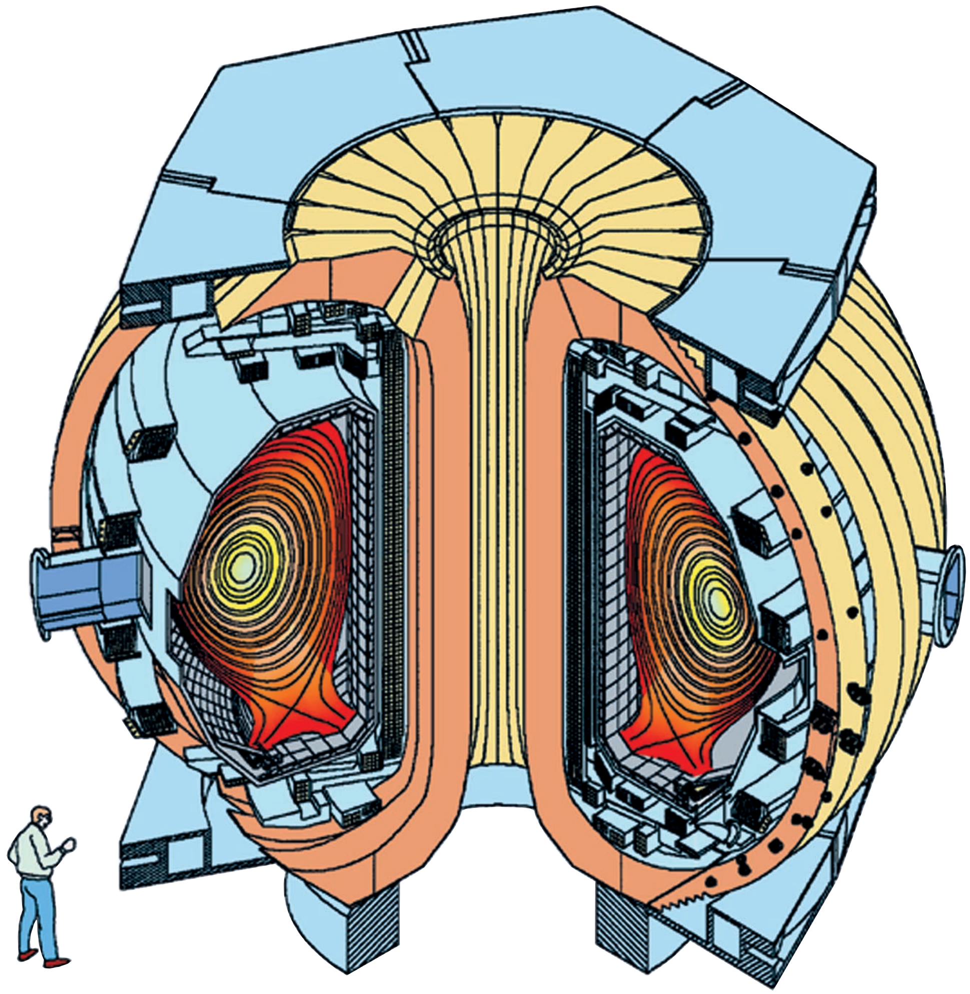
- *Two methods have been used to supplement the theoretical modeling*
  - *Global energy confinement scaling method*
  - *Dimensionless physics parameter similarity technique*

TOKAMAK: MAGNETIC CONFINEMENT

- **Toroidal magnetic field supplemented by a poloidal component produced by a large current in the plasma itself**
  - **Plasma current is induced by a transformer**

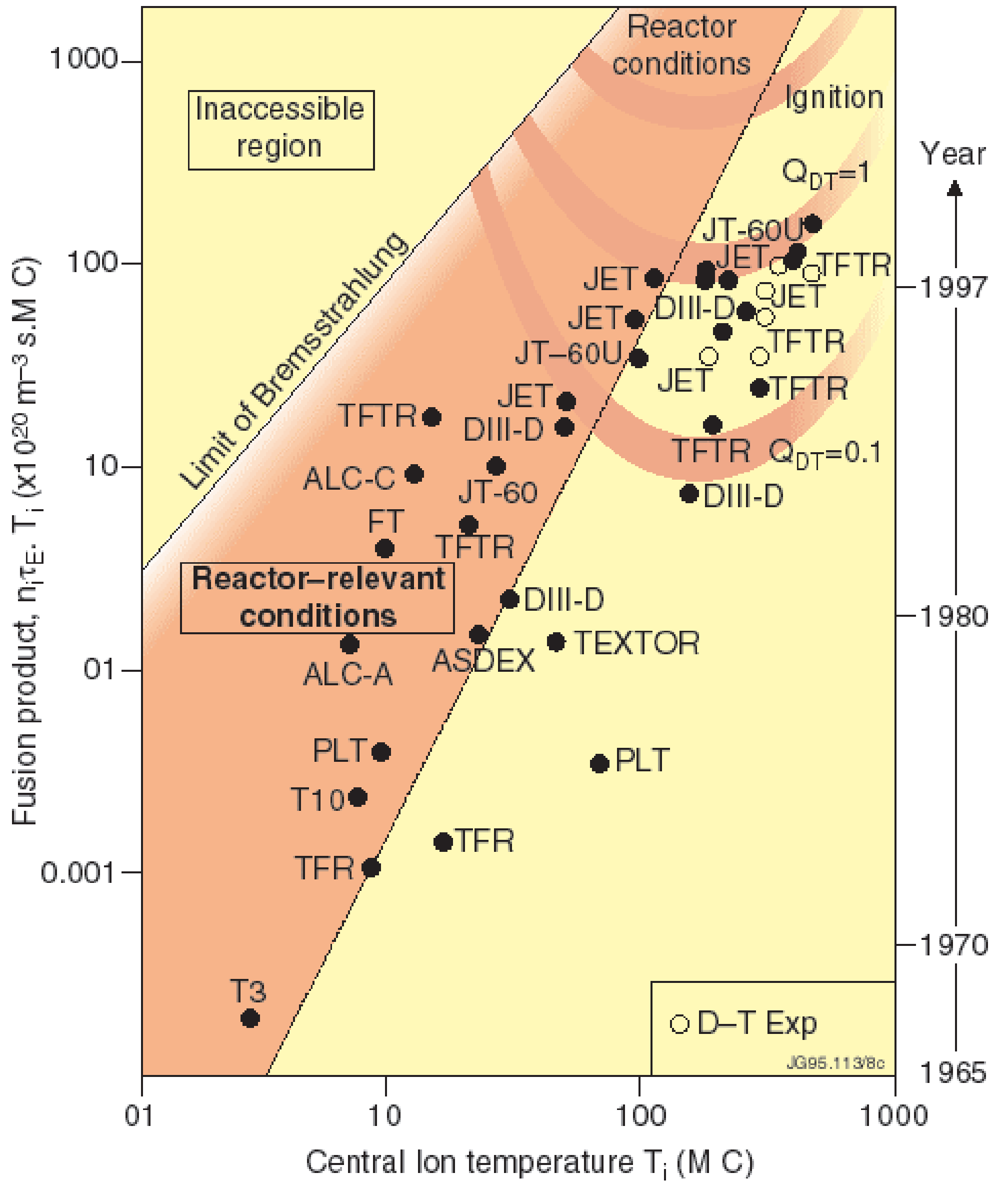


DEFINITION OF COMMON TERMS



- τ_E — Energy confinement time (s)
- I_p — Toroidal plasma current (amp)
- B_T — Toroidal magnetic field (T)
- P_{aux} — Auxiliary heating power (W)
- n_e — Electron density (m^{-3})
- A_i — Ion mass (atomic mass units)
- R — Tokamak major radius (M)
- a — Tokamak minor radius (m)
- κ — Plasma elongation

STEADY PROGRESS TO REACTOR CONDITIONS



K. Thomsen, et al., ICUS Press Workshop, 1998

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GENERAL ATOMICS

SUMMARY

- ***Statistical analysis of the energy confinement data***
  - *Virtues: Simplicity and a good track record of predicting behavior*
  - *Weaknesses: Ignore profile effects and possible hidden parameters*

- ***Dimensionless physics parameter similarity approach***
  - *Virtue: Profile effects are fully included*
  - *Weaknesses: Range in experimental ρ_* is small, need a larger experimental database, uncertainty about which are the key parameters*

- ***Full 1–D Modeling***
  - *Virtue: In principle all transport processes, sources, and sinks can be included*
  - *Weaknesses: Progress in modeling core, edge region still being worked on*

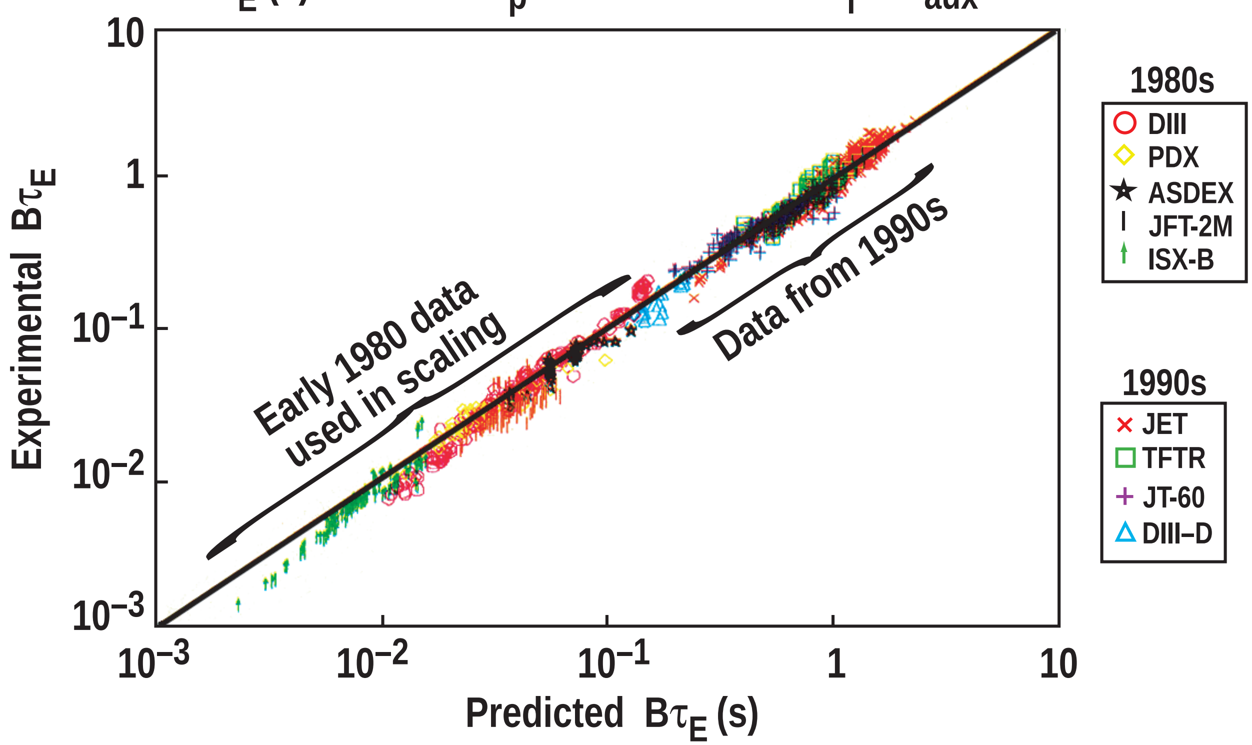
GLOBAL ENERGY CONFINEMENT SCALING

- *Yields an overview of the “physics terrain”*
- *Provides some basis for extrapolation to future devices*
- *Potential to give critical information for understanding the underlying nature of radial transport*
- *Empirical energy confinement scaling done in the form of a power law*
  - $\tau_E \propto a^x b^y c^z \ldots$
  - *a,b,c are plasma parameters*
  - *x,y,z are simple numerical exponents*

EARLY CONFINEMENT RELATIONSHIP

- 1982 data from small to medium size tokamaks (DIII, PDX, ASDEX, JET, JFT–2M, ISX–B)
  - $R = 0.9 – 1.6$ m, $a = 0.25 – 0.45$ m, $I_p = 100 – 600$ kA, $P_{aux} = 0.2 – 6$ MW
- 10 years later predicted confinement in much larger tokamaks
  - $R \sim 3$ m, $a \sim 1$ mm, I_p up to 7 MA, P_{aux} up to 30 MW
  - Mean error of 4% and an RMS spread of 12%

$$\tau_E\,(s) = 3 \times 10^{-5}\, I_p\, R^{1.75}\, a^{-0.37}\, R^{0.5}\, A_i^{0.5} / P_{aux}^{0.5}$$



J.G. Cordey, et al., Physics Today, Vol. 45 No. 1, 1992

HIGH MODE OR H–MODE CONFINEMENT SCALING

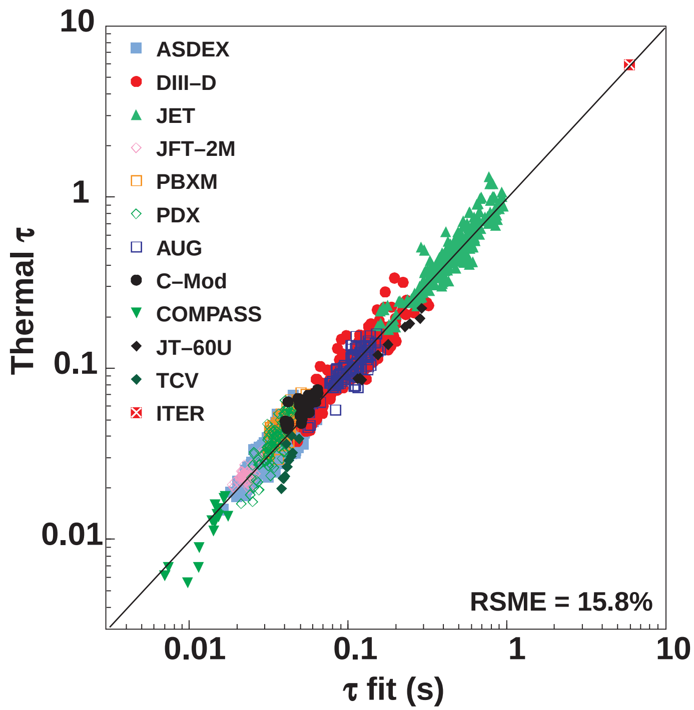
- *Plasma can transition to a higher energy confinement state*
  - *This states provides the framework for future machine design*

- *Empirical relationships have been used to study H–mode confinement*

- *Most recent work includes data from 13 tokamaks worldwide*
  - *1398 data points used in scaling*

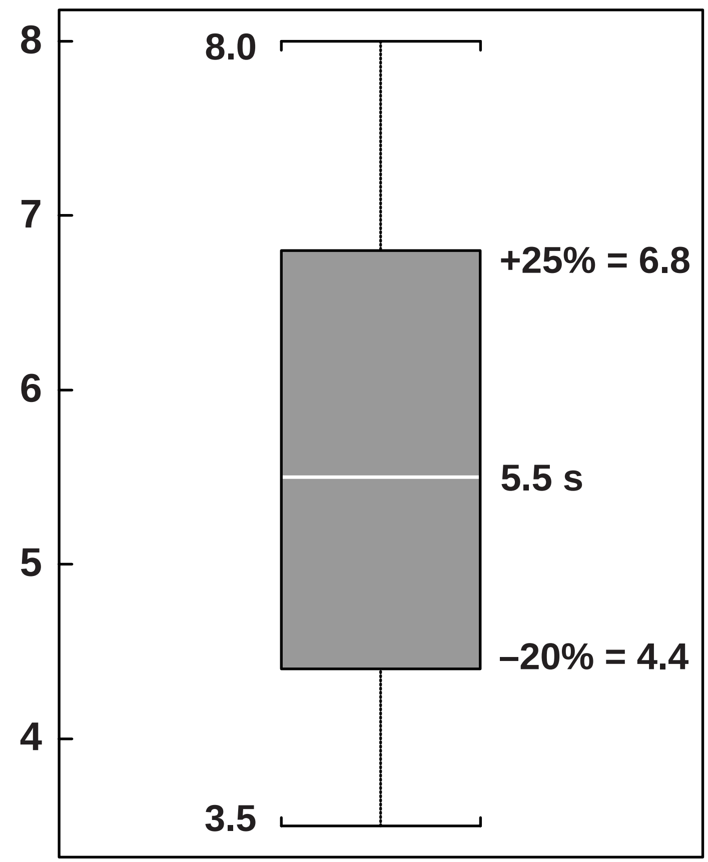
PRESENT DAY H–MODE CONFINEMENT SCALING

- Dataset spans confinement times over 2 orders of magnitude
- 95% confidence interval for power law form is $\delta\tau/\tau \approx \pm 17\%$



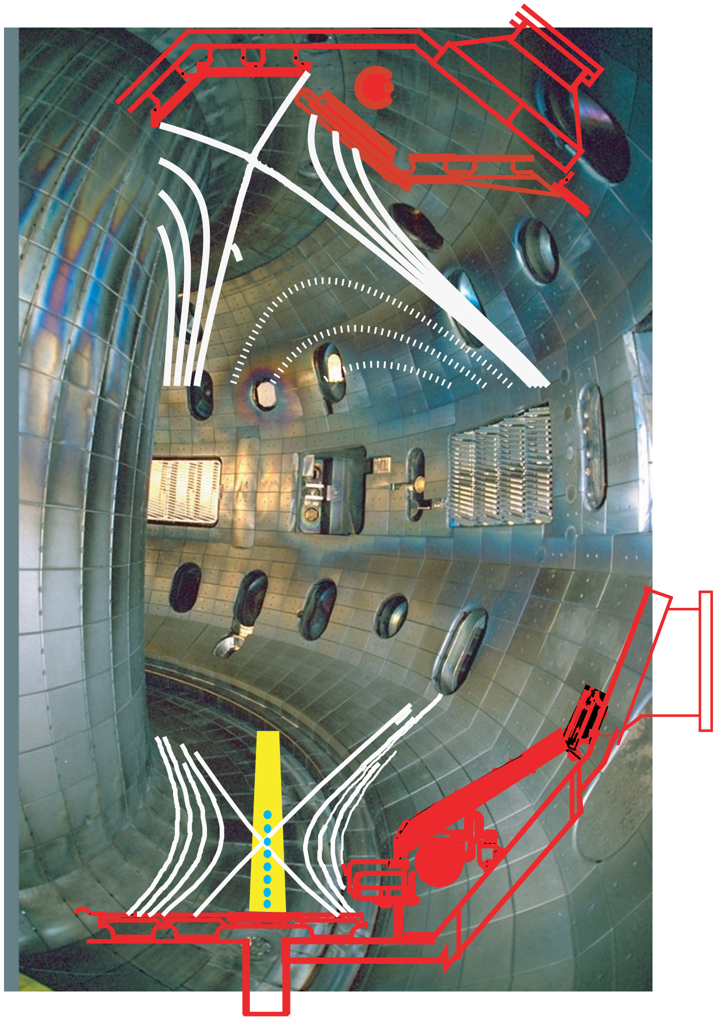
- $\tau_E = 0.03\ I_p^{0.89}\ B_T^{0.18}\ P_{aux}^{-0.64}\ N_e^{0.43}\ A_i^{0.13}\ R^{1.83}\ \varepsilon^{0.24}\ \kappa^{0.88}$

- $\delta\tau/\tau$ increases when other representations other than power law are considered



J.G. Cordey, et al., 17th IAEA Fusion Energy Conference (1998)
K. Thomsen, et al., 17th IAEA Fusion Energy Conference (1998)

DIMENSIONLESS SCALING OR WIND TUNNEL EXPERIMENTS



- For a future machine design, create discharges with the same shape and with as many dimensionless physics profiles matched

- Only ρ_* can not be matched and its scaling must be determined

T	—	Temperature
β	—	Particle to B pressure (nT/B^2)
ν_*	—	Collisionality (na/T^2)
q	—	Safety factor ($B_T a/B_p R$)
ρ_s	—	Larmor radius (mv/B)
ρ_*	—	Normalized gyroradius (ρ_s/a)
χ_B	—	Bohm diffusion (eT/cB)

DIMENSIONLESS PARAMETER SCALING TECHNIQUES

- *Significant progress has been made towards predicting and understanding radial heat transport using these techniques*

- *Two types of turbulent diffusion depending on step size*
  - *Macroturbulence: step or eddy size (Δ) on the order of the device size (a)*
  - *Microturbulence: Δ on the order of an intrinsic plasma parameter (ρ_s)*

- *Plasma diffusivity (χ) is proportional to a rate and a step size squared*

- *Expressing χ in its dimensionally correct form*
  - $\chi = \chi_B \, \beta^{\alpha_B} \, \nu^{\alpha_\nu} \, \rho_*^{\alpha_\rho} \, q_{95}^{\alpha_q} \, F(R/a, \kappa, T_e, T_i, \ldots)$
  - *F is an unknown function of all the other dimensionless parameters*
  - *For $\alpha_\rho = 1$ implies $\Delta = \rho_s$ which is called gyro–Bohm scaling*
  - *For $\alpha_\rho = 0$ implies $\Delta = a$ which is called Bohm scaling*
  - *For $\alpha_\rho = -1$ implies Δ » a which would arise from stochastic fields*

EXAMPLE OF A ρ_* SCALING EXPERIMENT

- *Plasma size and shape are held fixed and B and T change to vary only ρ_**

- *For a change in B, to keep β, ν_*, and q constant*
  - $n \propto B^{4/3}$
  - $T \propto B^{2/3}$
  - $I \propto B$

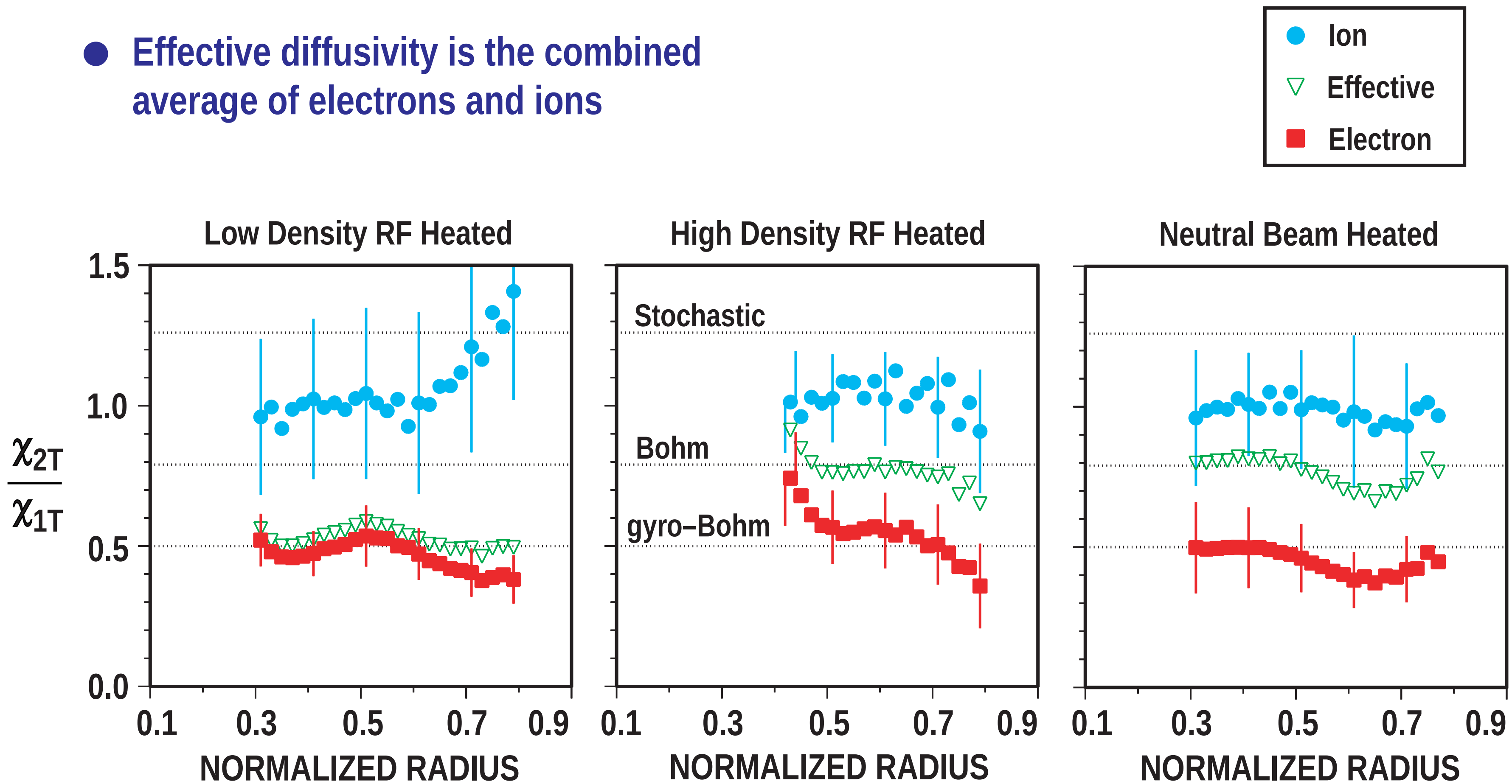
- *The effective charge (Z_{eff}), ion mass, T_e/T_i, heating profiles, and the density and temperature scale lengths should also be held constant*

- *Variation in ρ_* is proportional to $B^{-2/3}$*

- *Experiment varied B from 1 to 2 T*
  - *Dimensionless parameters well matched*
  - *ρ_* varies by 1.6 as expected*

ρ_* SCALING OF ION AND ELECTRON SPECIES IS DIFFERENT

- Electrons scale as gyro–Bohm
- Ions scale between Bohm and stochastic
- Effective diffusivity is the combined average of electrons and ions



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T. Luce, et al., Physica Scripta Vol. 52 (1995)

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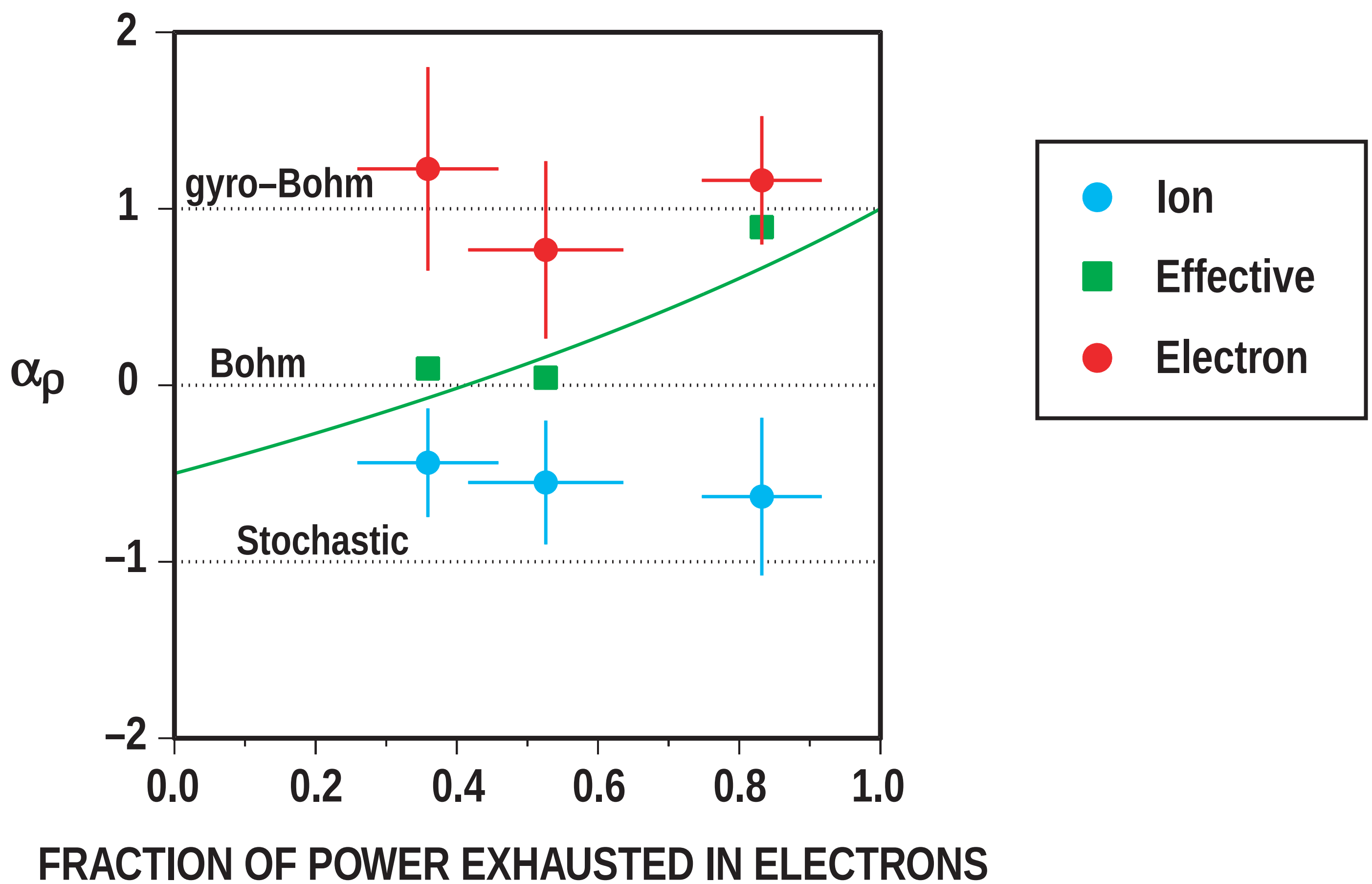
IONS AND ELECTRONS SCALE DIFFERENTLY THAN THE GLOBAL AVERAGE

- For the beam heated case, the global scales like Bohm when neither species does
- Global is the weighted average, by power flow, of the individual species



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C. Petty, et al., Phys. Rev. Lett. Vol 74, No.10 (1995)

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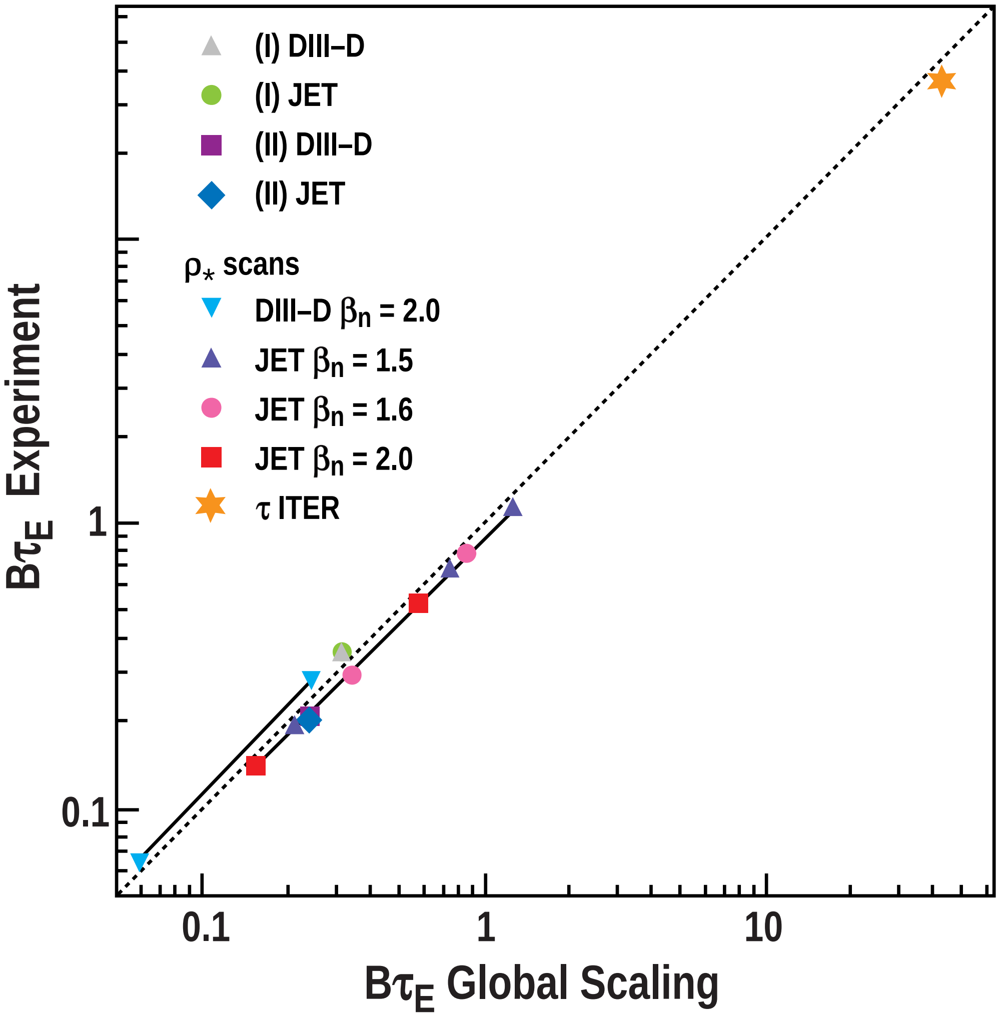
SINGLE PARAMETER ρ_* EXTRAPOLATION TO FUTURE MACHINES IS FEASIBLE



- Presently range in ρ_* is too small in one machine to predict a large future machine
- Uncertainty will be reduced by a joint ρ_* scan on at least two machines of different sizes
- Small scale turbulence and electrostatic (weak β)

$$\tau_E \propto B^{-1}\,\rho_*^{-3.15}\,\beta^{0.03}\,\nu^{-0.42}\,q_{95}^{-1.43}$$

$$\propto I_p^{0.84}\,B^{0.39}\,n^{0.18}\,p_{aux}^{-0.41}\,L^{2.00}$$

PREDICTIVE TRANSPORT MODELING

- *Objective*
  - *Predict temporal evolution of existing experiments*
  - *Gain insights into the physics governing transport*
  - *For future devices: extrapolate, investigate profile effects, and study new regimes — none of which can be done by global scaling laws*
- *Historically, transport models have been constructed from purely empirical observations of experimental data*
  - *Limited predictive capability due to a narrow range of observations*
- *Lately, considerable progress has been made in understanding the underlying physics governing confinement*
  - *Focus on anomalous (turbulence driven) transport*
  - *Improvements in computer code technology*

A LARGE GROUP OF MODELS ARE BEING TESTED

Model	Model Providers	Physics
Weiland	J. Weiland (EU)	ITG
Multimode	J. Kinsey, G. Bateman (US)	Drift waves, RBM, kinetic ballooning, neoclassical
Waltz GLF23	R. Waltz, J. Kinsey (US)	ITG
IFS/PPPL, no $E\times B$; IFS/PPPL, $E\times B$	B. Dorland (US)	ITG
CDBM	A. Fukuyama (JA)	Current diffusive ballooning modes
RLW B, RLW	D. Boucher (JCT)	Semi-empirical
Culham	M. Turner (EU)	Semi-empirical
Mixed	A. Taroni (EU)	Semi-empirical
Mixed-shear	G. Vlad/M. Marinucci (EU)	Semi-empirical
T11/SET	A. Polevoi (RF)	Semi-empirical
CPTM	Yu. Dnestrovskij (RF)	Semi-empirical

A LARGE DATABASE HAS BEEN ASSEMBLED FOR USE IN MODEL VALIDATION

- *Represents an open and systematic procedure for assessing the performance of transport models against well documented data*

- *Database consists of 209 discharges from 12 different tokamaks*

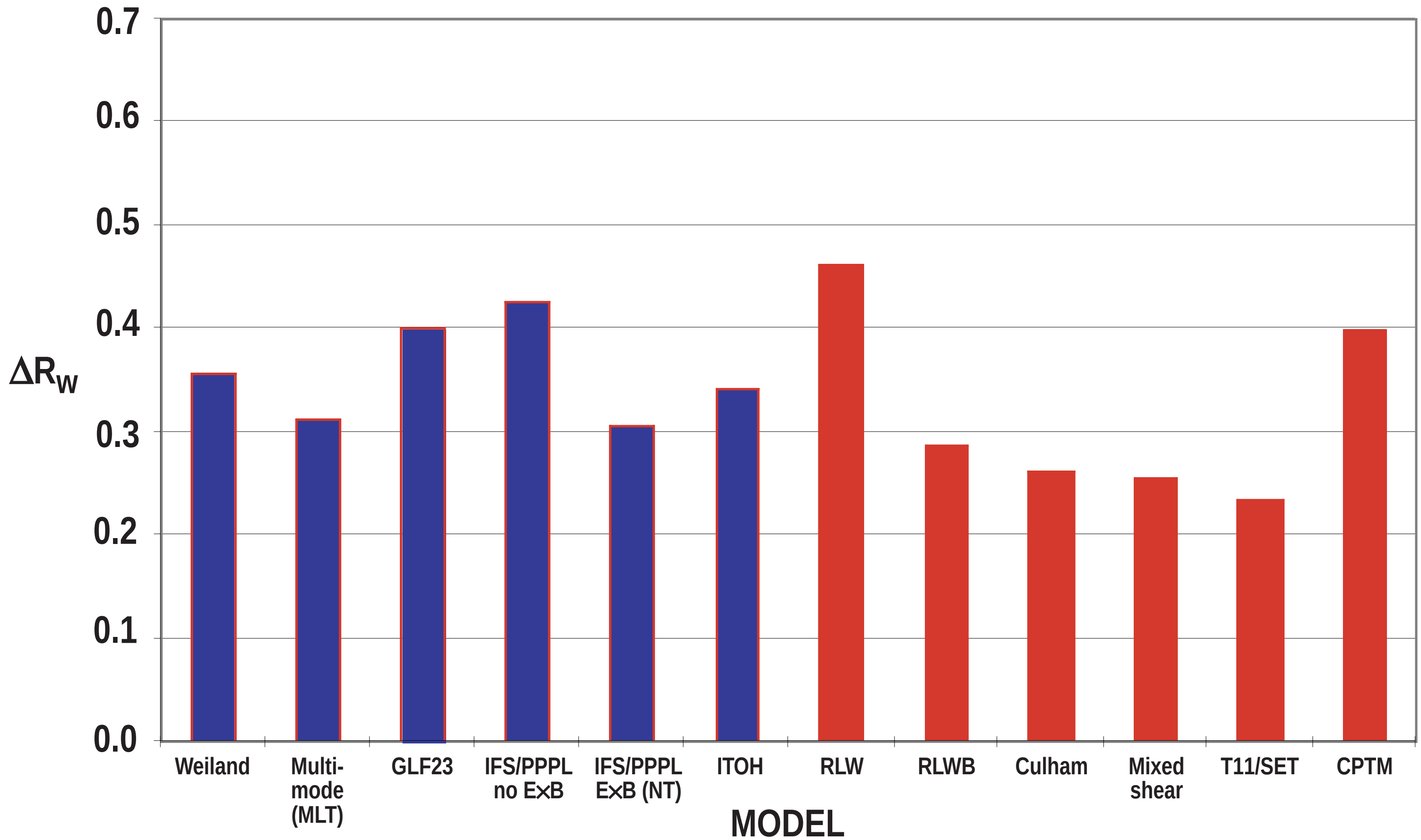
- *Eleven transport models are being tested by a larger number of modelers*

- *Quantitative comparison is made between the model prediction and the experimental data for both global and local quantities*

AVERAGE ERROR IN STORED ENERGY PREDICTION

- ΔR_W is the average error in the total plasma stored energy

$$\Delta R_W = \sqrt{\sum_i \left(\frac{W_{si}}{W_{xi}} - 1\right)^2 / N}$$



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J. Kinsey, et al., APS/DPP Meeting (1998)

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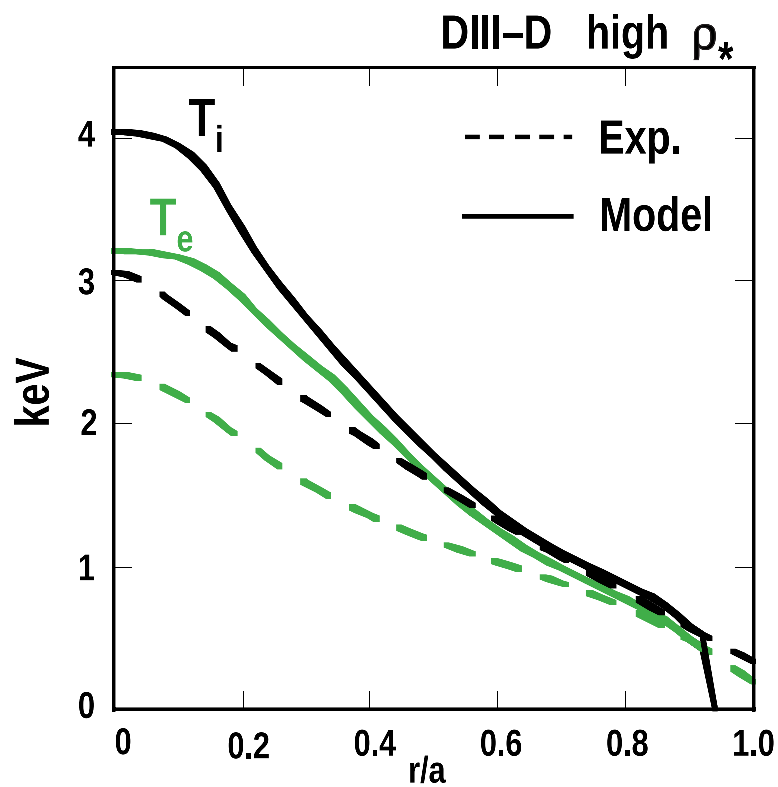
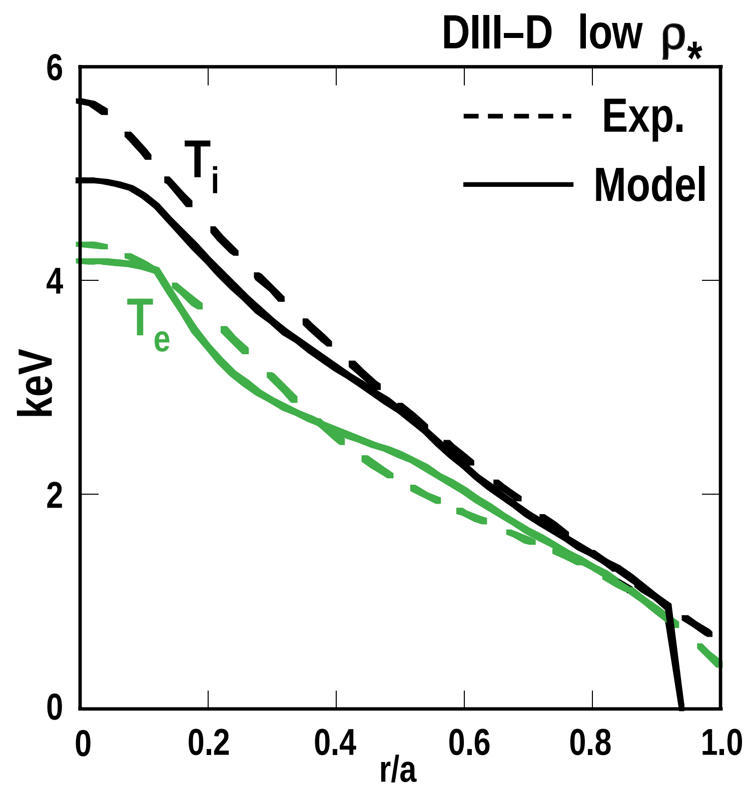
A PLASMA EDGE PEDESTAL MODEL IS REQUIRED

- Present transport models deal in the plasma interior (r/a < 0.9)
- Predictions of future machine performance depend critically on the edge temperature

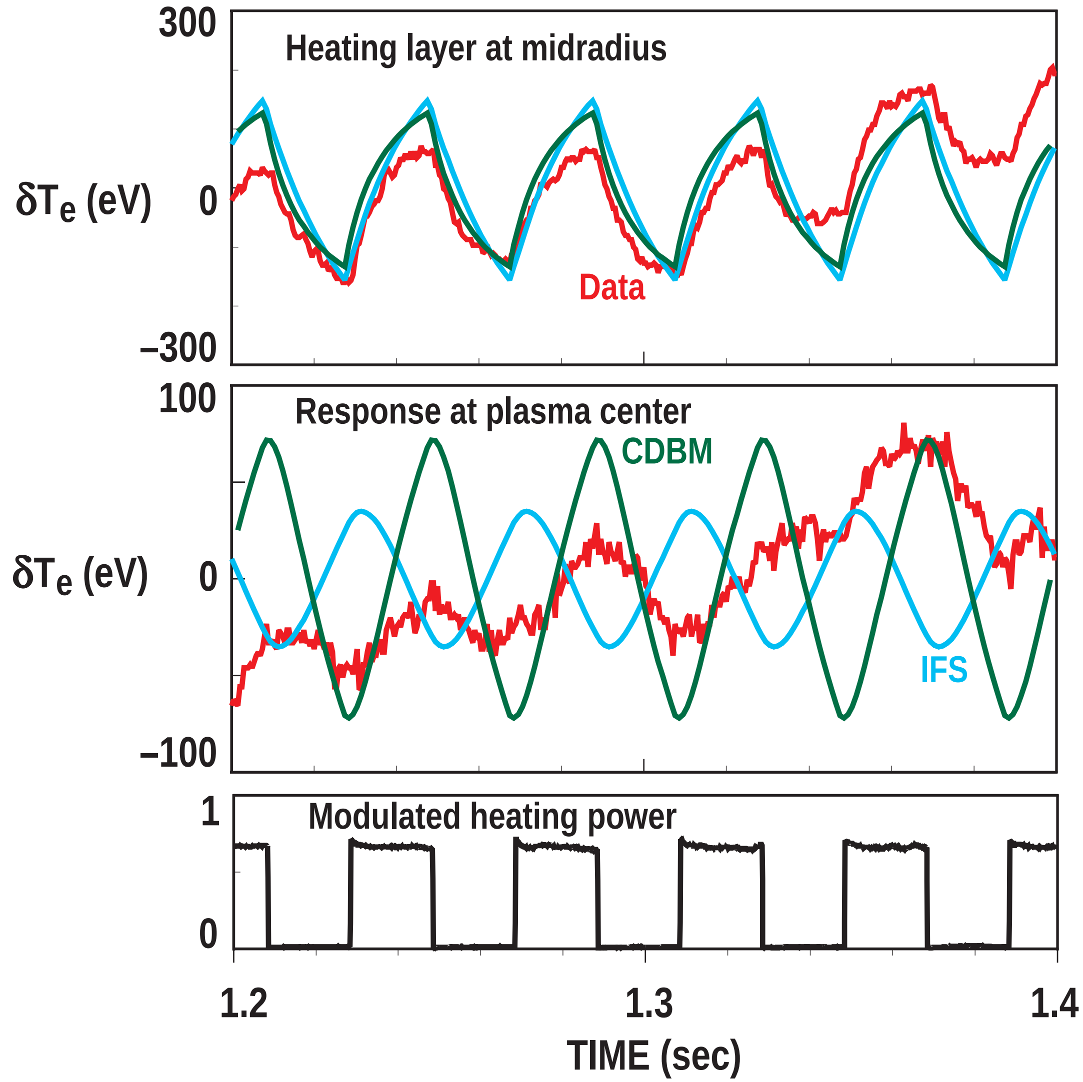




R. Waltz, et al., Phys. Plasmas (1998)

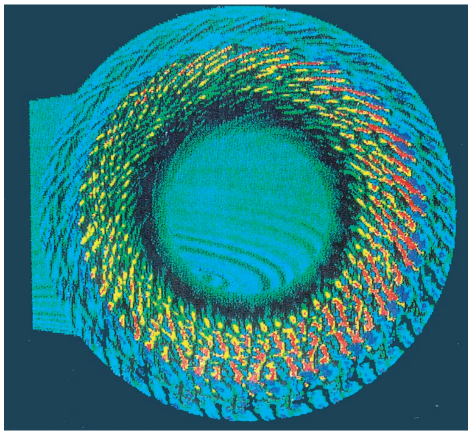
MODELS RESPONSE TO MODULATED HEATING PROVIDES A MORE SENSITIVE VALIDATION TECHNIQUE

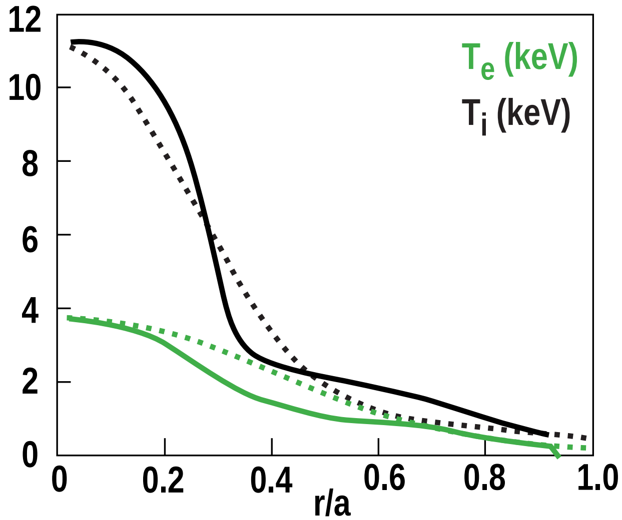
- Electron repsonse to modulated ECH is measured with a fine temporal and spatial resolution
- Two different physics models predict similar behavior at the heating location but different behavior at the plasma center



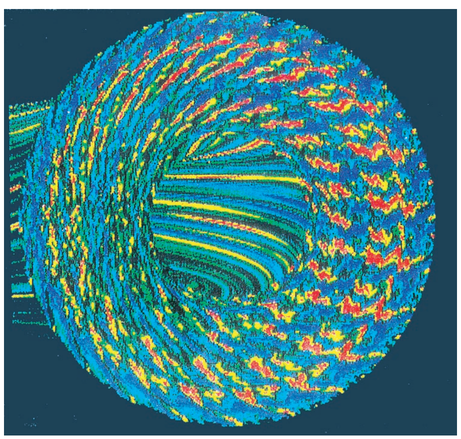
MODELS ARE EVOLVING AS FURTHER PHYSICAL EFFECTS ARE INCLUDED

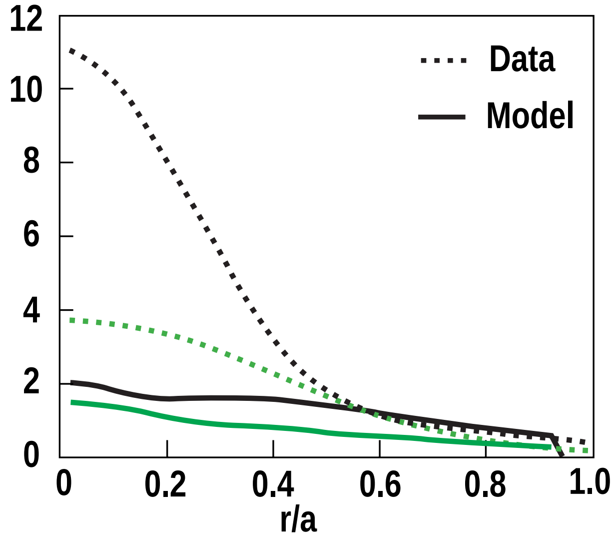
With E × B flow shear





Without E × B flow shear





R. Waltz, et al., Phys. Plasmas 1 (1994)

- Gyrofluid simulation of toroidal ITG turbulence
- Turbulence decorrelation and stabilization by sheared E×B flow
- Application of E×B shear breaks up eddies and considerably reduces transport by a factor of ten
- For details see Burrell's talk at this conference (WB21.04 ,Thursday 15:30)