I. INTRODUCTION

- Among the endless surprises that the tokamak plasma has provided us, the formation of the transport barrier in the plasma interior is the least expected and the most interesting one

- Inside the transport barrier the ion thermal diffusivity, deduced from experimental observations, has come down to, should we say, almost nothing. In other words, it is to the bottom level suggested by the ideal theory,

$$\chi_{(\mathrm{EXPERIMENTAL})} \approx \chi_{(\mathrm{NEOCLASSICAL})}$$

This led to the general belief that the transport barrier is the direct consequence of the instability suppression. Apparently, the suppression is so complete that the plasma has to rely upon the classical mechanism to transport heat.

- The barrier can be formed inside of an L–mode plasma to convert it into the so called ITB plasma with an L–mode edge. Or, as observed recently in many tokamaks, the barrier can also be formed inside the so called quiescent H–mode (QH–mode) plasmas. In this case there are two barriers, one ITB and the other edge transport barrier (ETB), hence the plasma is called quiescent double barrier (QDB) discharge. These discharges are noted for their capability for good energy confinement, for instance,

$$\beta_N H_{89} = 7 \text{ for } 10\,\tau_E \ .$$

- It is of interest to speculate how would the ITB and QDB plasmas respond to the changes in global plasma parameters. The present study is an attempt to model these plasmas along this particular line of inquiry.

- The model presented here divides the plasma into three regions: the central, the interior and the edge. The transport barrier is with the interior region. In the case of H–mode, the edge has its own edge barrier.

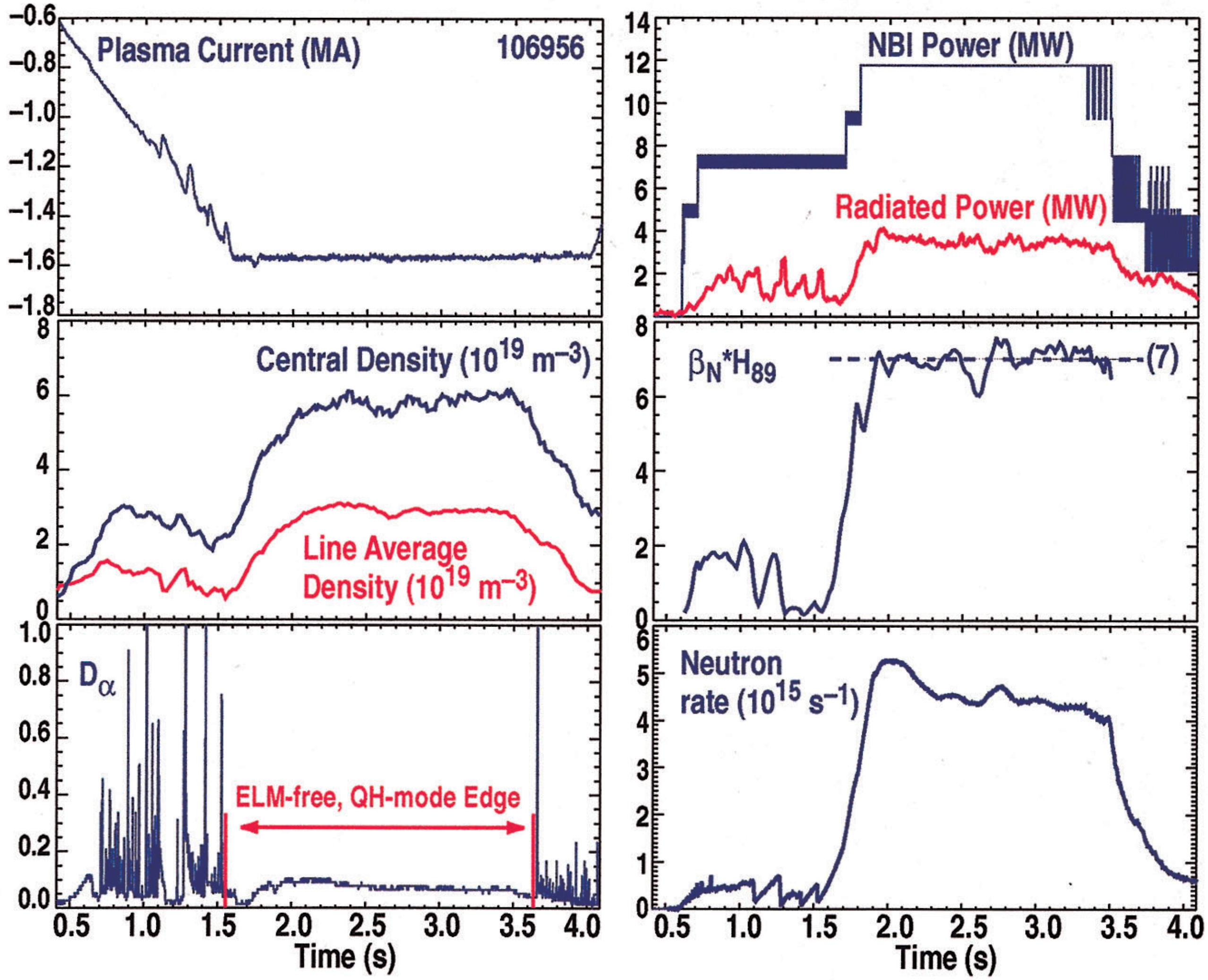
- **Thermal diffusivity selection plays a key role in this model. The model assigns different thermal diffusivities to these plasma regions, for instance, neoclassical diffusivity to the interior region. However, it becomes much involved to determine and justify the diffusivity selection for L–mode and H–mode plasmas.**

- **With the selected thermal diffusivities and a given set of input plasma parameters, the model proceeds to calculate the radial plasma temperature distribution and the associated global energy confinement time.**

- **It is our intent for the model to be simple and analytic. To be able to obtain analytic expressions along the way requires simplicity. For simplicity, the plasma is treated as a single fluid, for instance. The analytic expression helps us to trace the connection among the plasma parameters.**

COMBINATION OF CORE ITB AND QH-MODE EDGE RESULTS IN SUSTAINED HIGH PERFORMANCE

- $\beta_N H_{89}$=7 for 10 τ_E (1.6 s)
- β=3.9%
- Example of quiescent operation without EHO, but with global 1/1 mode
- Same performance obtained in discharges with EHO



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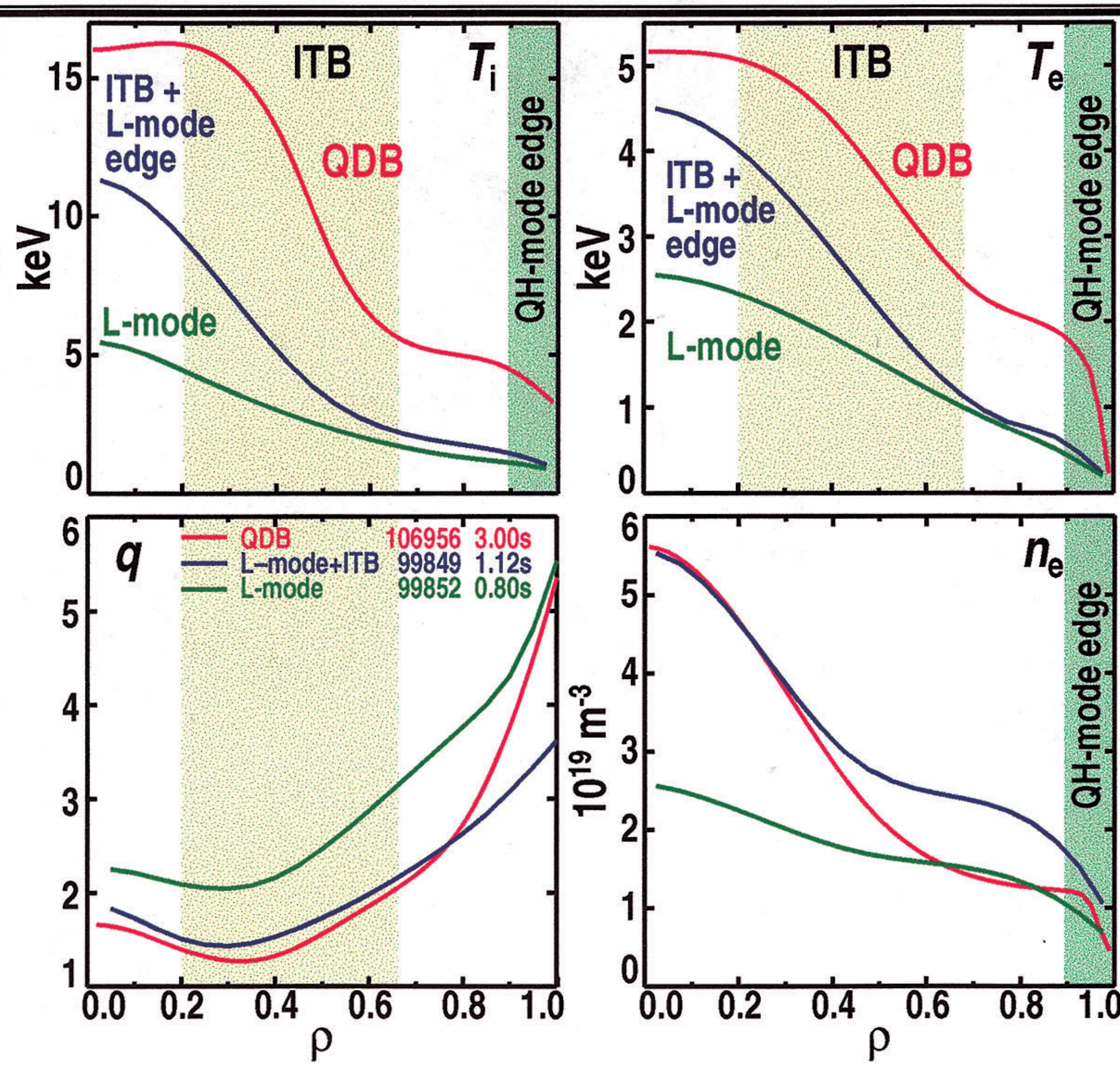
QDB REGIME COMBINES CORE TRANSPORT BARRIER WITH QUIESCENT EDGE BARRIER — "QUIESCENT DOUBLE BARRIER"

- Edge pedestal elevates central temperatures, improving fusion performance



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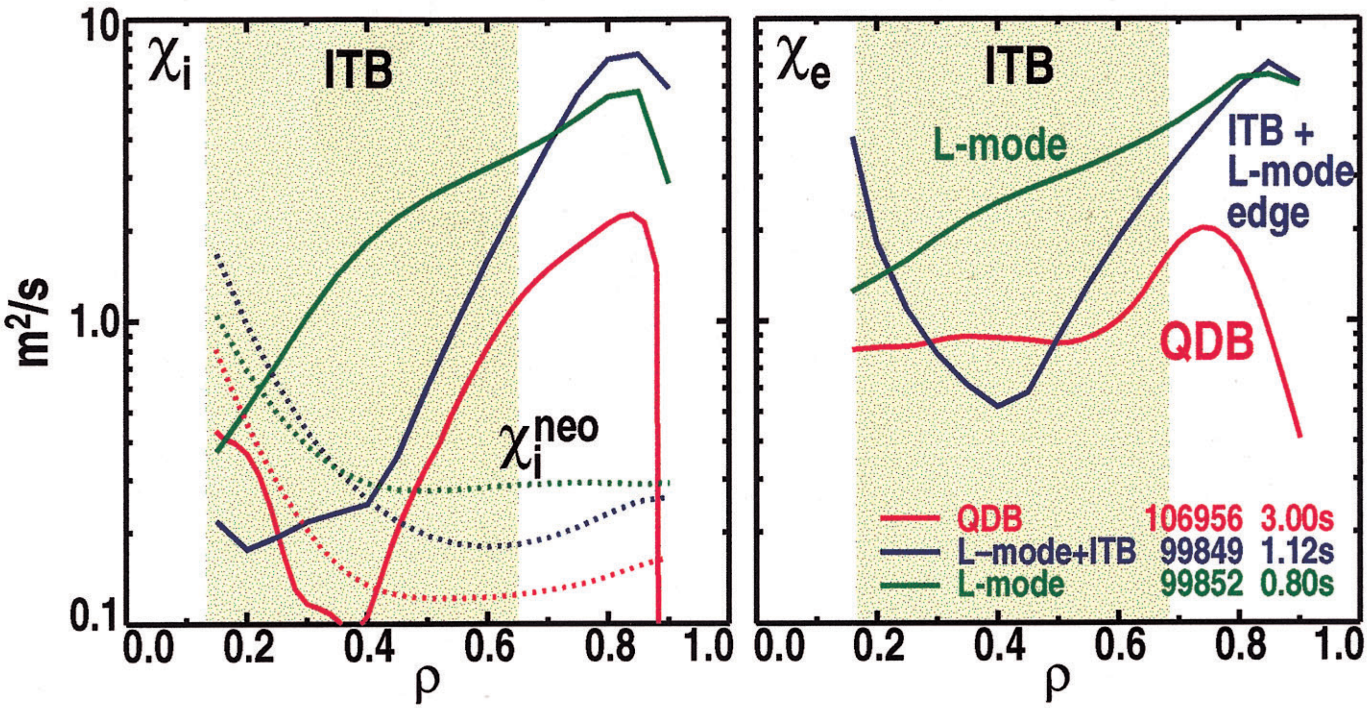
TRANSPORT ANALYSIS CONFIRMS PRESENCE OF DOUBLE (CORE AND EDGE) TRANSPORT BARRIERS



- Core transport is similar to that in ITB plasmas with an L-mode edge
  - ITB refers to region of reduced transport relative to L-mode
- Edge transport is typical of H-mode
- Core and edge barriers are kept separate by region of low ExB shear

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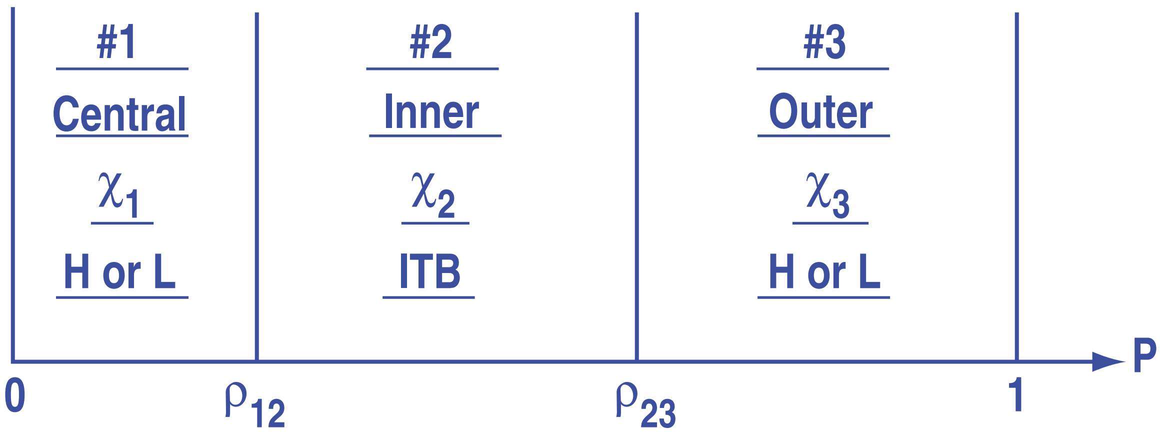
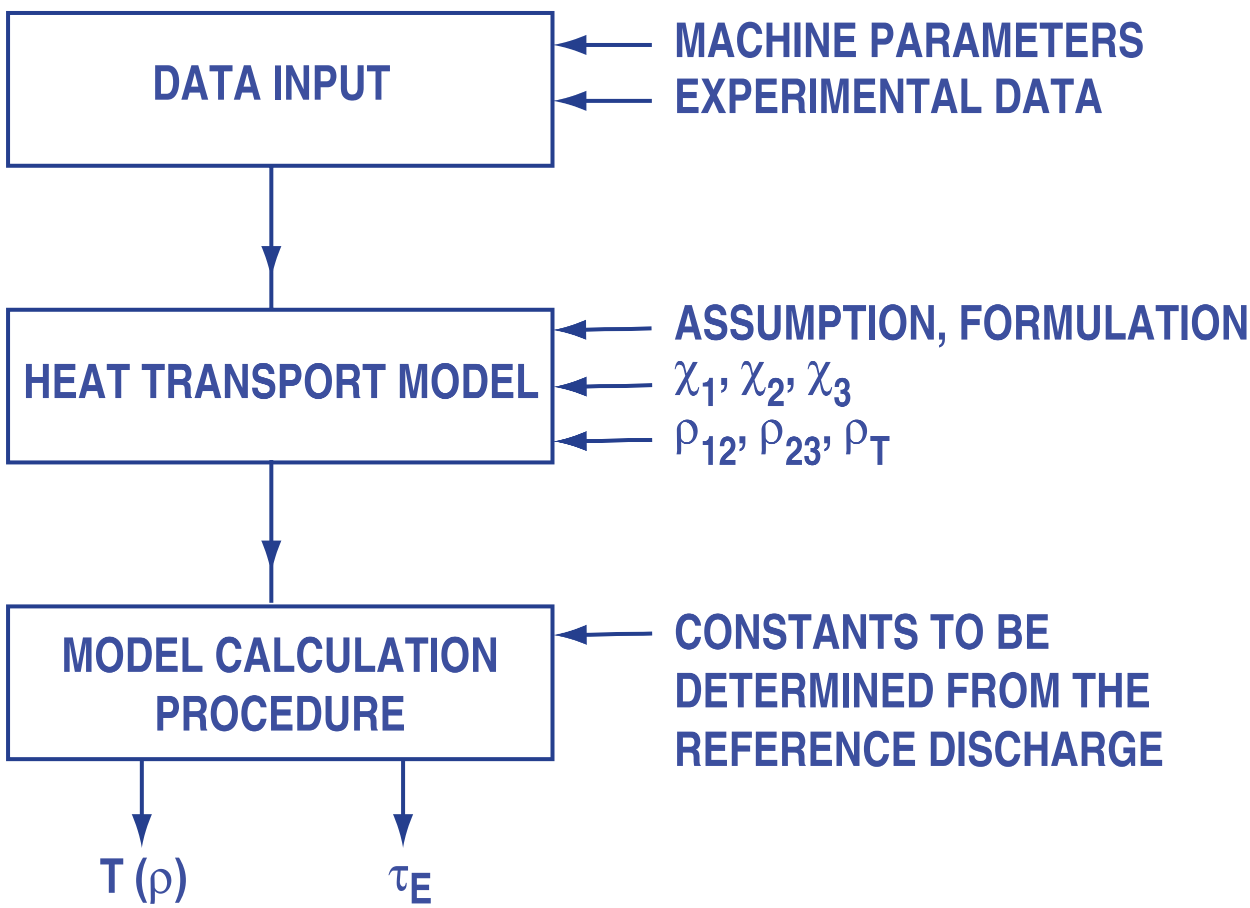
ITB CONFINEMENT SCALING MODEL





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II. THERMAL DIFFUSIVITIES

- For thermal diffusivities that can be expressed in a certain function form, the heat diffusion equation allows the global parameters to be separated from their profile distributions. As a result, the global energy confinement scaling can be derived through the diffusion equation and expressed in an analytic form.

- For instance, by taking the neoclassical diffusivity in the function form below, and going through the heat diffusion equation,

$$\chi_{\mathrm{neo}} \propto n^{1} T^{-1/2} B_{\mathrm{p}}^{-2} r^{1/2} R^{-1/2} \quad ,$$

$$-\frac{1}{\rho}\left(\frac{\partial}{\partial\rho}\right)\rho n \chi_{\mathrm{neo}} \frac{\partial T}{\partial\rho} = a^{2} p(\rho) \quad , \qquad 0 < \rho < 1 \quad ,$$

the energy confinement scaling can be obtained as,

$$\mathcal{T}_{\mathrm{neo}} = Z_{\mathrm{c}} Z_{\mathrm{GS}} Z_{\mathrm{PF}} \quad ,$$

$$Z_{\mathrm{GS}} = \frac{I^{4} P^{1}}{n^{3} a^{3}} \quad ,$$

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- In comparing with

$$\mathcal{T}_{89} \propto \frac{n^{0.1}\, I^{0.85}\, R^{1.2}\, a^{0.3}\, B^{0.2}\, M^{0.5}}{P^{0.5}} \quad ,$$

the H factor for the neoclassical is,

$$\mathcal{H}_{\text{neo}} = \frac{\mathcal{T}_{\text{neo}}}{\mathcal{T}_{89}} \propto \frac{I^{3}\, P^{1.5}}{n^{3}\, a^{3.3}\, R^{1.2}\, B^{0.2}} \quad .$$

Clearly, the global parameters can have a strong influence on the H factor.

- The thermal diffusivity for L–mode plasmas is selected entirely based on experimental observations. In a previous work for modeling L–mode plasma, we determined the diffusivity expression below and its associated energy confinement scaling as the best choice to reproduce both the measured electron temperature profile and the global energy confinement data,

$$\chi_L \propto \frac{nT^{3/2}}{B_p^2} r^3 \left(\frac{1}{T}\frac{\partial T}{\partial r}\right)^2 ,$$

$$\mathcal{T}_L \propto \frac{n^{0.2} I^{0.8} a^{0.8} R^{0.6}}{P^{0.6}} .$$

The diffusivity reproduces also the profile resilience observed in various experiments. The effect of profile resilience comes mainly from the diffusivities dependence on the temperature gradient length.

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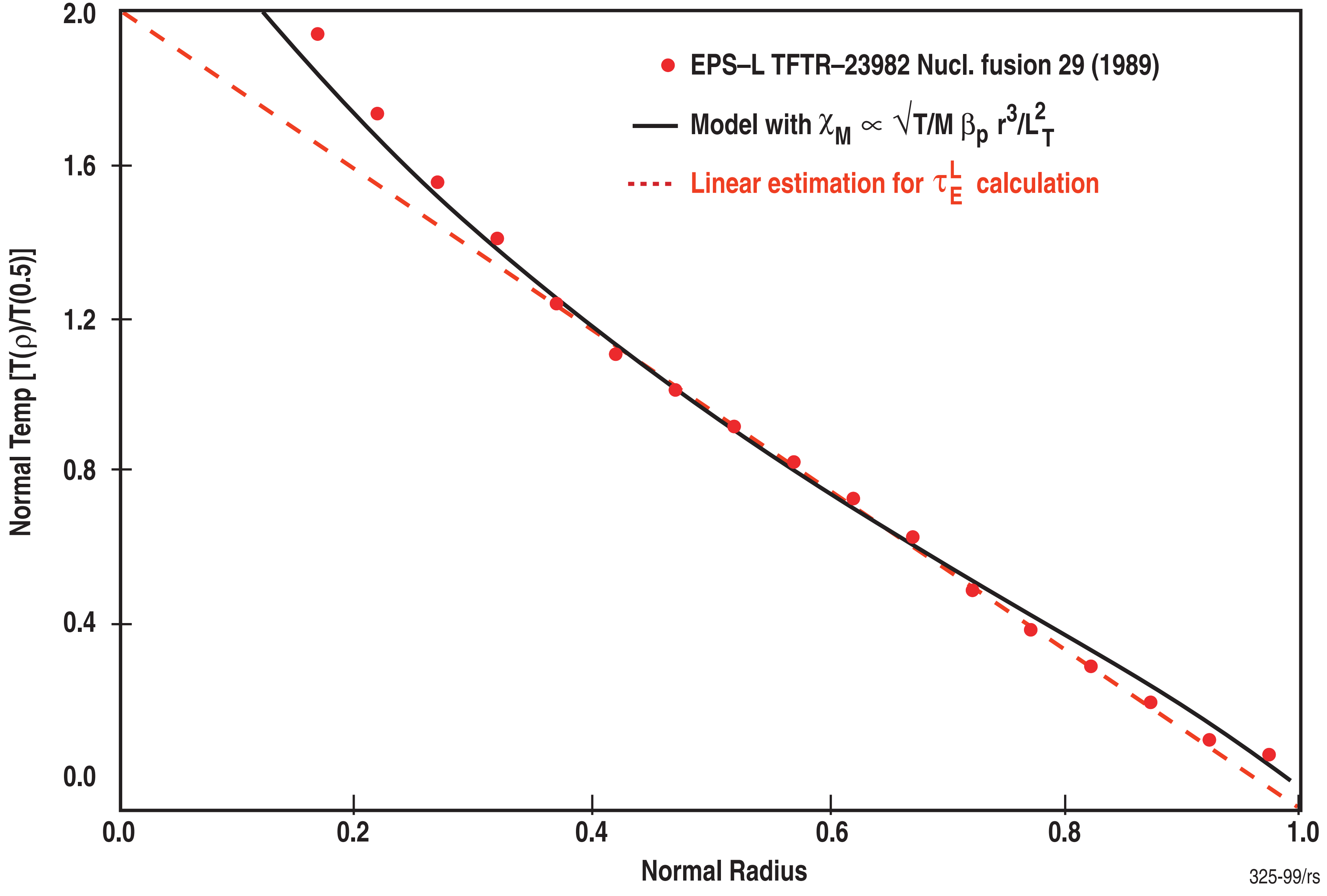
- In a previous work for modeling H–mode plasma, we showed that the H–mode plasma can be considered as a larger L–mode plasma with its outer layer stripped away. In essence, the two modes have the same heat transport process (the same diffusivity for both modes) and the only difference is their boundary condition. As a matter of fact, a new function form was worked out for the energy confinement scaling, which consists of two terms to include the boundary effect. Hence, for H–mode plasma the present model employs,

$$\chi_H = \chi_L \propto \frac{nT^{3/2}}{B_p^2} r^3 \left(\frac{1}{T} \frac{\partial T}{\partial r} \right)^2 \quad ,$$

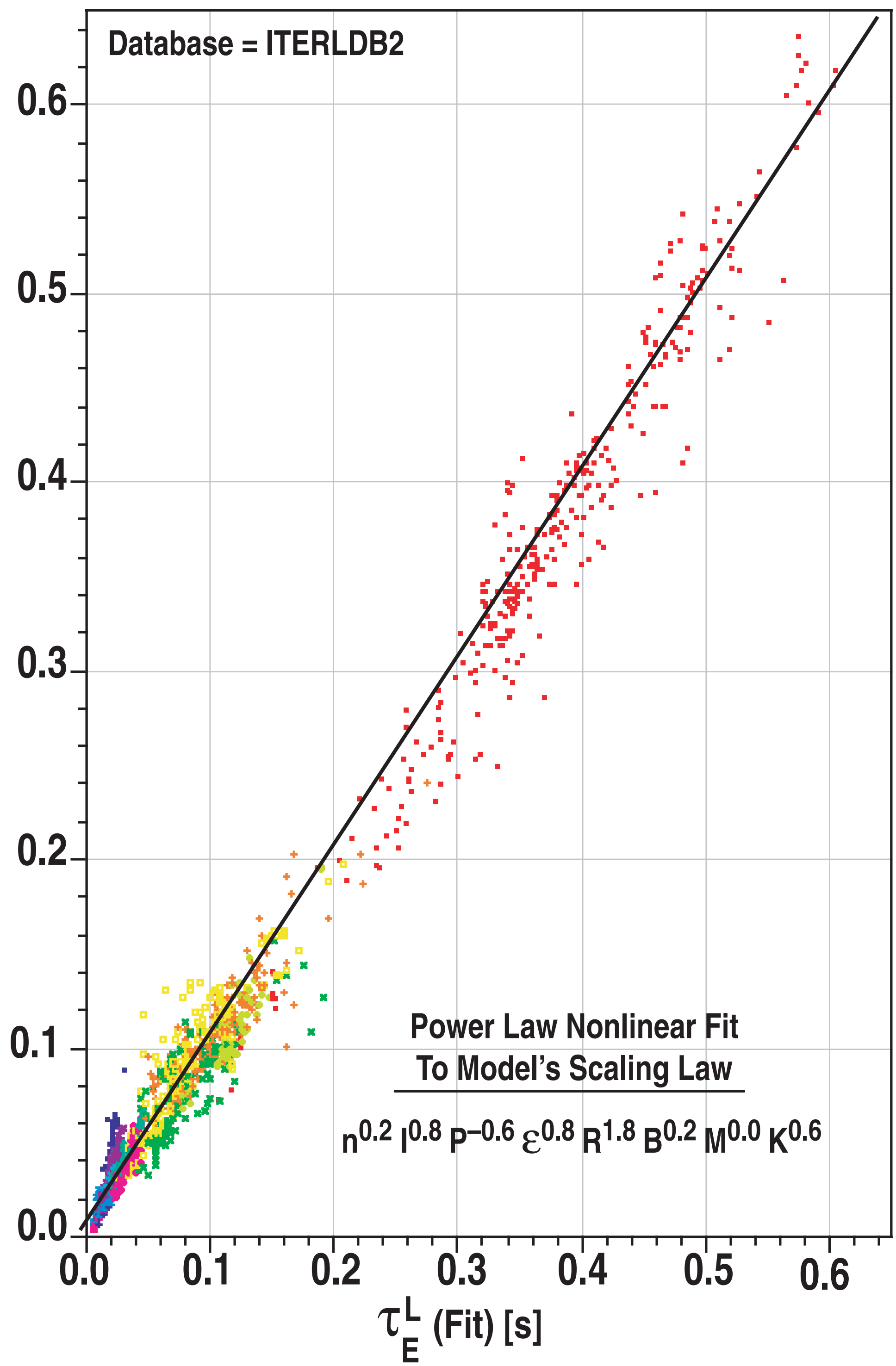
$$\mathcal{T}_H = \mathcal{T}_L (1+B) \quad .$$

The new H–mode scaling agrees fairly well with the ITER H–mode confinement database.

T_e PROFILE SHAPE OF AN L–MODE PLASMA



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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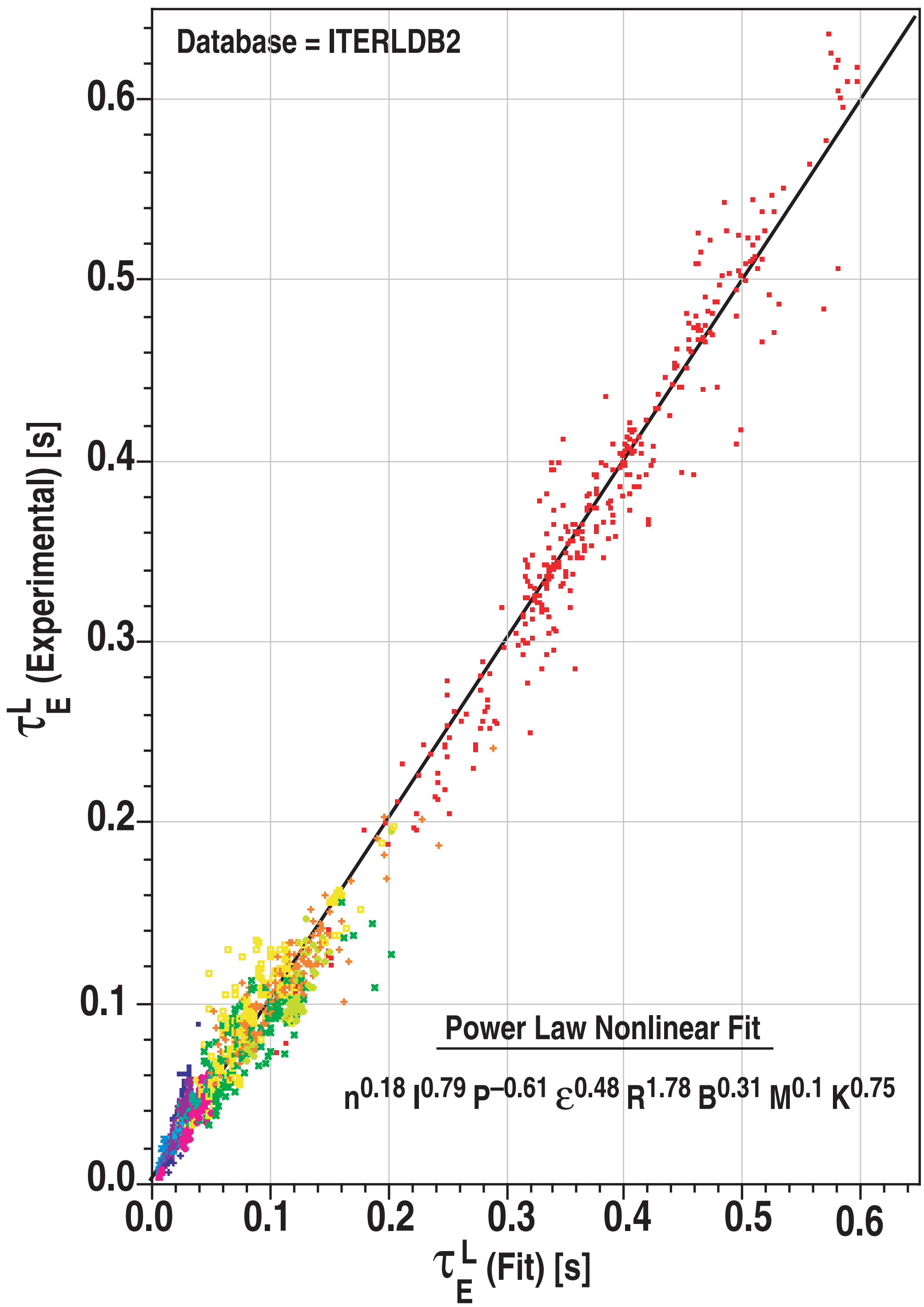
τ_E^L POWER LAW NONLINEAR FIT TO ITERDB2 CONFINMENT DATABASE



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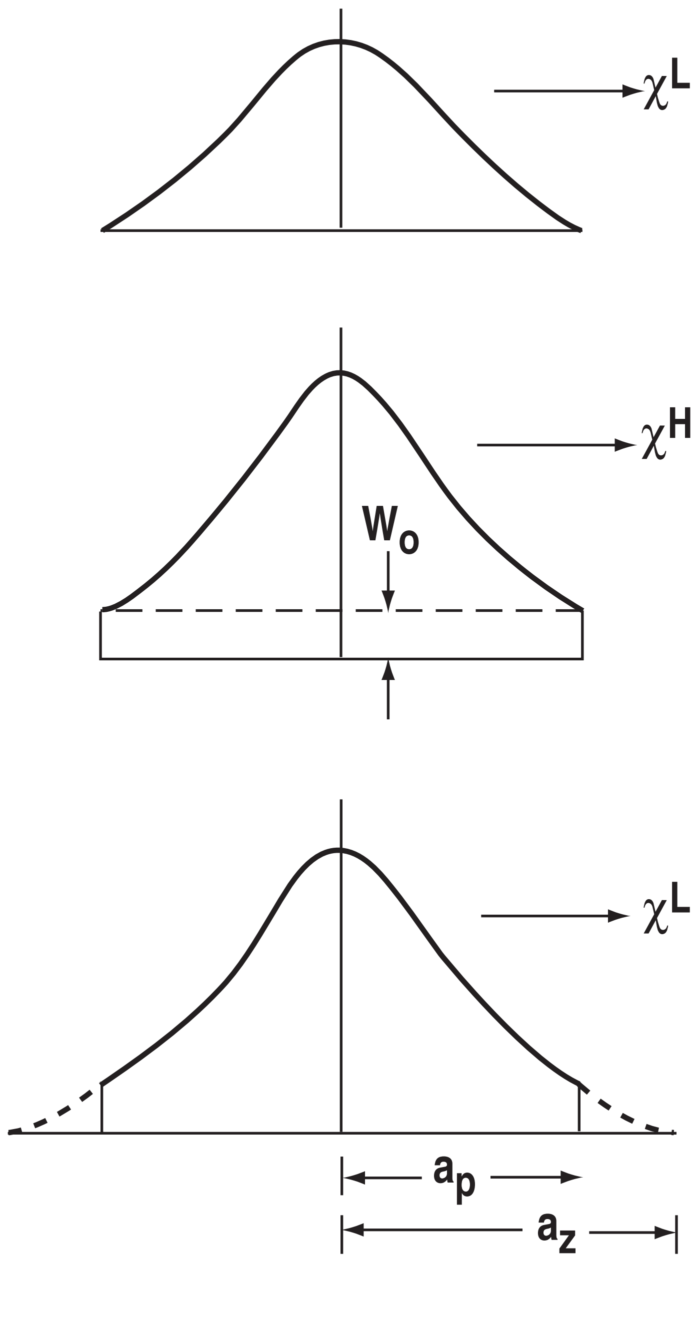
τ_E^H REPRESENTATION WITH DIFFERENT VIEWPOINTS



L–mode

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

H–mode

$$\tau_E^H = \prod_P \chi_i^{Vi} \quad \textbf{(a)}$$

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

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

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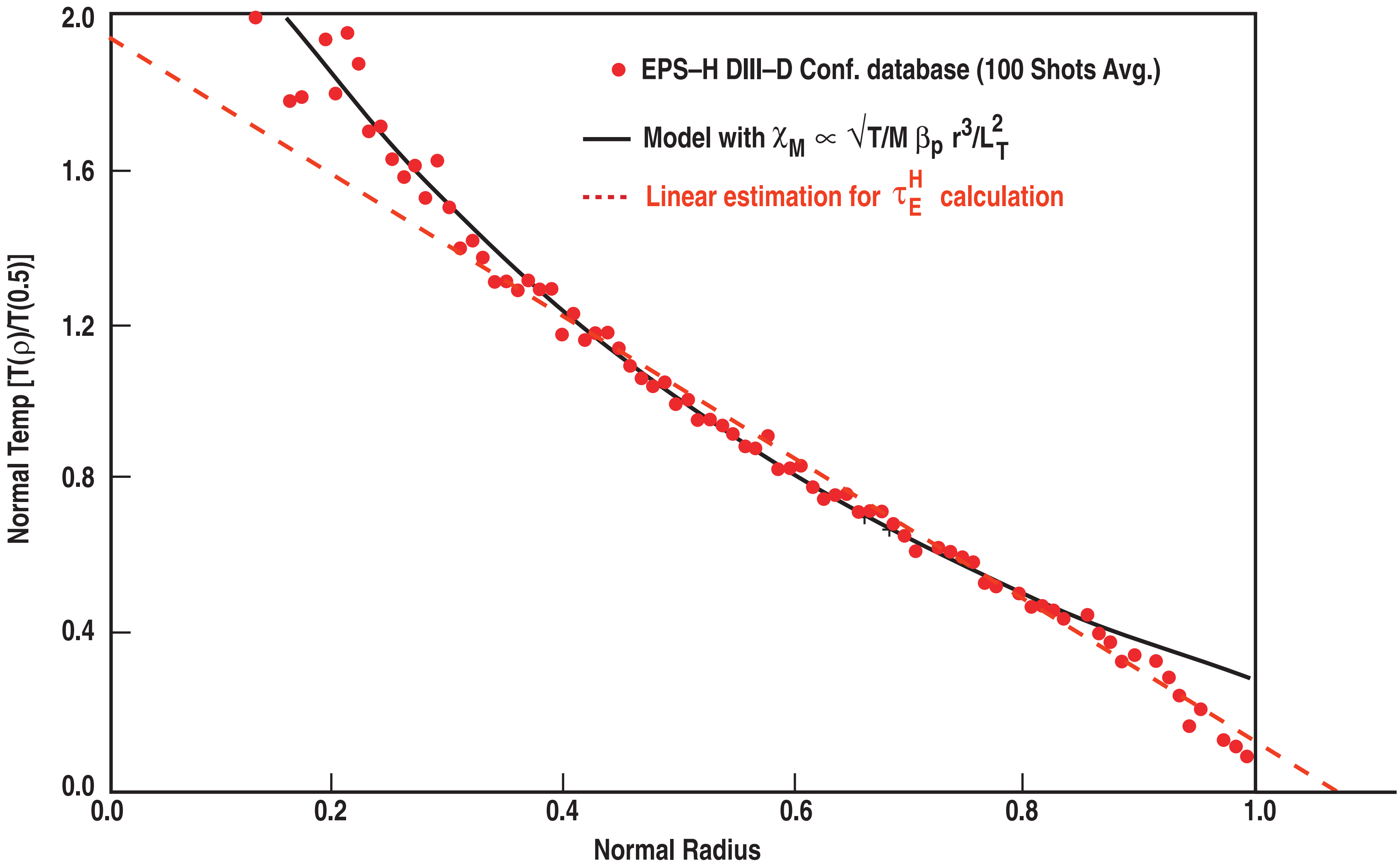
T_e PROFILE SHAPE OF H–MODE PLASMAS



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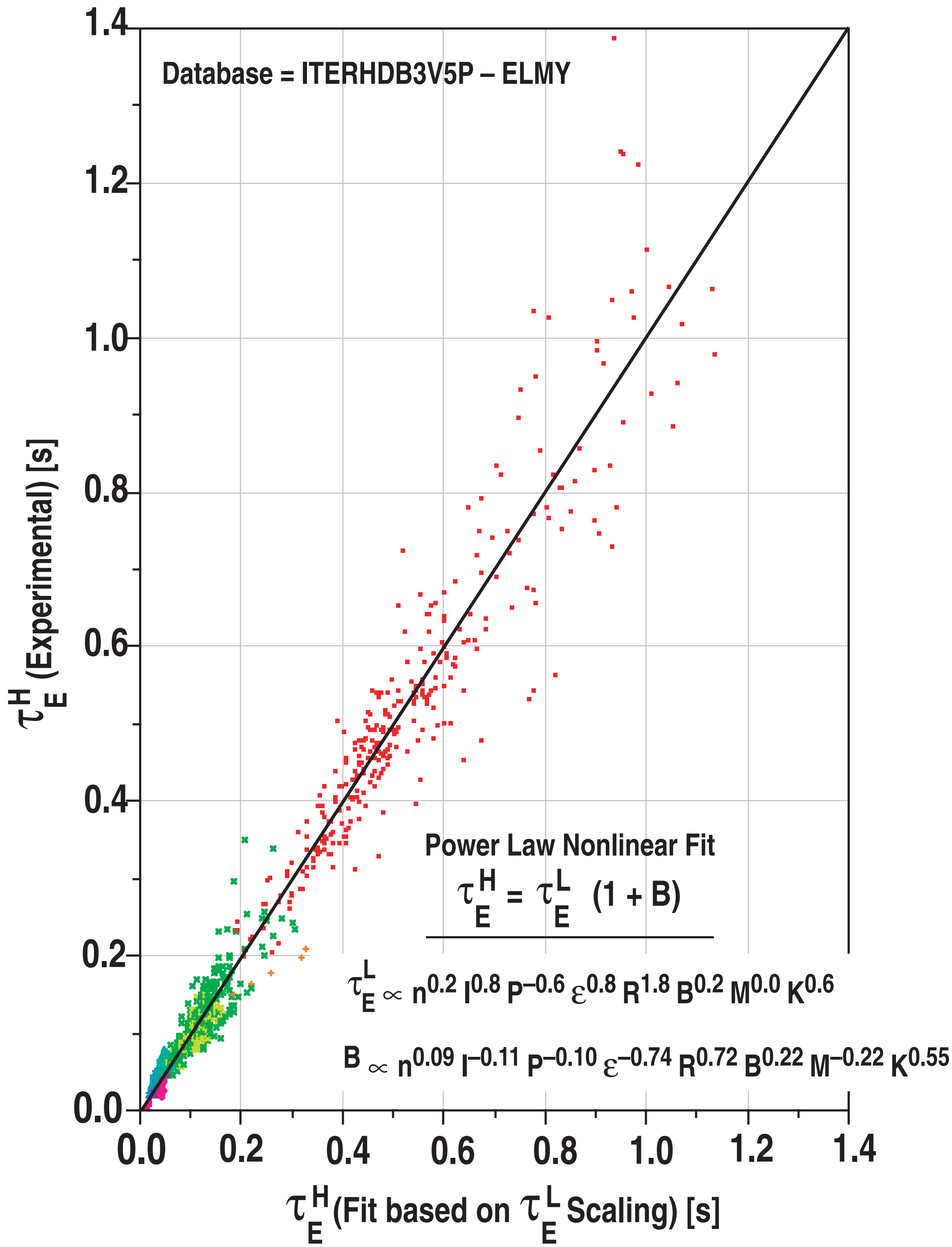
τ_E^H — BASED ON τ_E^L SCALING OF A TRANSPORT MODEL — POWER LAW NONLINEAR FIT TO DATABASE ITERHDB3V5P–ELMY



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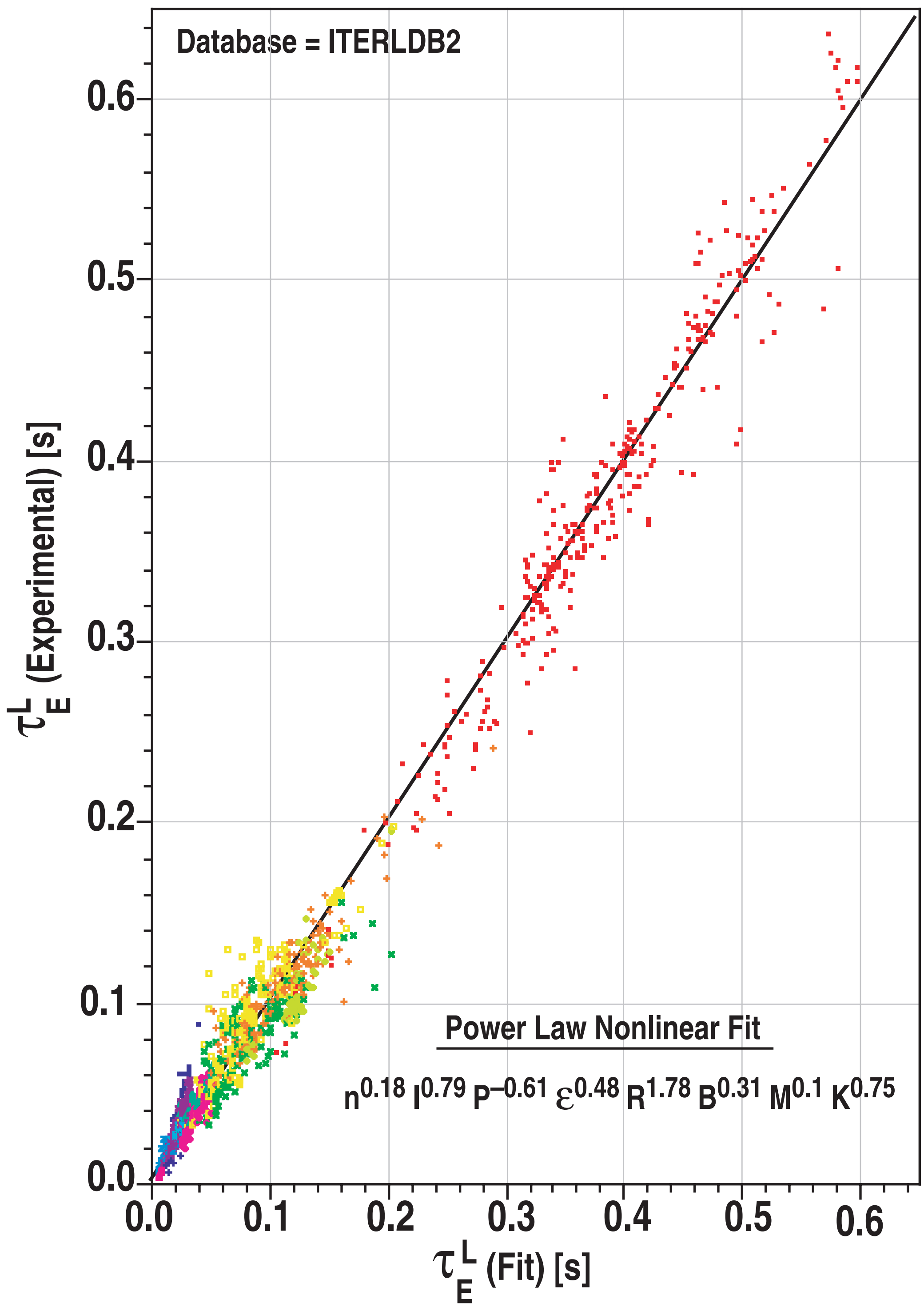
τ_E^L POWER LAW NONLINEAR FIT TO ITERDB2 CONFINMENT DATABASE



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III. MODEL AND SOLUTION

- The model assumes the plasma as a single fluid. In other words, it assumes essentially that the transport barrier works equally well for both electrons and ions since it does not distinguish the individual species. Other assumptions includes the circular plasma crossection, and the heat conduction as the primary heat transport process. The process is represented by,

$$-\frac{1}{\rho}\left(\frac{\partial}{\partial\rho}\right)\rho n \chi \frac{\partial T}{\partial\rho} = a^2 p(\rho) \quad , \qquad 0<\rho<\rho_T \quad ,$$

and the thermal diffusivities for the three plasma regions as,

$$\chi \;=\; \chi_1 \propto\; nT^{-1/2} B_p^{-2}\; r^3 \left(\frac{-\partial T}{\partial r}\right)^2 \quad , \qquad 0<\rho<\rho_{12} \quad ,$$

$$=\; \chi_2 \propto\; nT^{-1/2} B_p^{-2}\; r^{1/2}\; R^{-1/2} \quad , \qquad \rho_{12}<\rho<\rho_{23} \quad ,$$

$$=\; \chi_3 \propto\; nT^{-1/2} B_p^{-2}\; r^3 \left(\frac{-\partial T}{\partial r}\right)^2 \quad , \qquad \rho_{23}<\rho<\rho_T \quad ,$$

- **Input parameters**
  - Global: I_o, P_o, a, R, B_T
  - Radial distributions:
    - Power deposition profile, $p(\rho)$
    - Density profile, $n(\rho) = \bar{n}h(\rho)$
    - Q profile, $q(\rho) = q_a\, g(\rho)$.
  - Regional: $(\rho_{12}, \rho_{23}, \rho_T)$, (f_1, f_2, f_3).

- **Solutions for temperature**
  - Region 3

$$T_3(\rho) = C_{T_3}\left(\frac{I_o^2\, P_o}{\bar{n}_3^2\, a^2\, R}\right)^{2/5}\left[\int_{\rho}^{\rho_T}\left(\frac{F_3(y)}{y^2 \bullet g^2(y)}\right)^{1/3}\right]^{6/5},$$

with $F_3(\rho) = f_1 + f_2 + f_3\left(\dfrac{\rho^2 - \rho_{23}^2}{1 - \rho_{23}^2}\right)$.

— Region 2

$$T_2(\rho) = \left[\mathrm{T}_3^{1/2}(\rho_{23}) + C_{\mathrm{T}_2} \left(\frac{I_0^2 \, P_0}{\overline{n}_2^2 \, a^{5/2} \, R^{1/2}} \right) \int_{\rho}^{\rho_{23}} \frac{y^{1/2} F_2(y)}{h^2(y) \, g^2(y)} \, dy \right]^2 \quad ,$$

with $F_2(\rho) = f_1 + f_2 \left(\dfrac{\rho^2 - \rho_{12}^2}{\rho_{23}^2 - \rho_{12}^2} \right) \quad .$

— Region 1

$$T_1(\rho) = \left[\mathrm{T}_2^{5/6}(\rho_{12}) + C_{\mathrm{T}_1} \left(\frac{I_0^2 \, P_0}{\overline{n}_1^2 \, a^3 \, R} \right)^{1/3} \int_{\rho}^{\rho_{12}} \left[\frac{F_1(y)}{y^2 \bullet g^2(y)} \right]^{1/3} dy \right]^{6/5}$$

,

with $F_1(\rho) = f_1 \dfrac{\rho^2}{\rho_{12}^2} \quad .$

- **Solutions for energy confinement time**

$$\tau_E = \frac{2\,k_{\mathcal{T}}\left(2\pi^2 R\,a^2\right)\left(w_1 + w_2 + w_3\right)}{P_o} \quad ,$$

with

$$w_1 = \int_o^{\rho_{12}} n_1(\rho)\,T_1(\rho) \bullet \rho\; d\rho\;\rho \quad ,$$

$$w_2 = \int_{\rho_{12}}^{\rho_{23}} n_2(\rho)\,T_2(\rho) \bullet \rho\; d\rho\;\rho \quad ,$$

$$w_3 = \int_{\rho_{23}}^{1} n_3(\rho)\,T_3(\rho) \bullet \rho\; d\rho\;\rho \quad .$$

- The confinement scaling of the outer region is similar to that of the L- or H-mode. For instance, it can be shown,

$$\mathcal{T}_3 = \frac{w_3}{P_o} = Z_c\, Z_{GS}\, Z_{PF} \quad ,$$

$$\mathcal{T}_3 \propto Z_{GS} = \frac{n_3^{1/5}\, I_o^{4/5}\, a^{4/5}\, R^{3/5}}{P_o^{3/5}} \quad .$$

The effect of inside regions to the outer region comes from the power received in these regions which has to come out through the outer region.

- The confinement scalings of the inside regions are somewhat complicated by the fact that they have to work on the platform of the temperature and density built by the outer region. In other words, what the outer region does affects the operation condition of the inner regions.

IV. MODEL CALCULATION AND RESULTS

- **The calculation procedure follows:**
  - Pick a reference shot from the ITB or QDB discharges obtained in DIII-D.
  - Besides the global parameters, as input to the model, approximate the radial distribution of safety factor *q* to obtain the B_p. Approximate also the power deposition profile and the density profile.
  - Try to match up the measured temperature profile, thereby determine the constant in the diffusivity expressions.
  - Vary the global parameter input to see how does the energy confinement time responds.

- Which temperature profile to match? The options are the ion profile or the combined $(T_e + T_i)/2$ profile. The ion has a profile too flat in the outer region for a good match. The difference is less pronounced in the combined case, but the barrier effect is much reduced because of the electron.

- The detail of temperature matching is not expected to change the qualitative trend that the individual plasma parameter makes to the global energy confinement time.

- Using DIII-D shot# 106956, a QDB discharge, as the reference shot, the model calculated the scaling trends of the confinement by varying the global parameters P_{in}, I_p and n_p. One interesting feature to note immediately is that the confinement does not degrade continuously with increasing P_{in}, very much unlike what the plasma used to do.

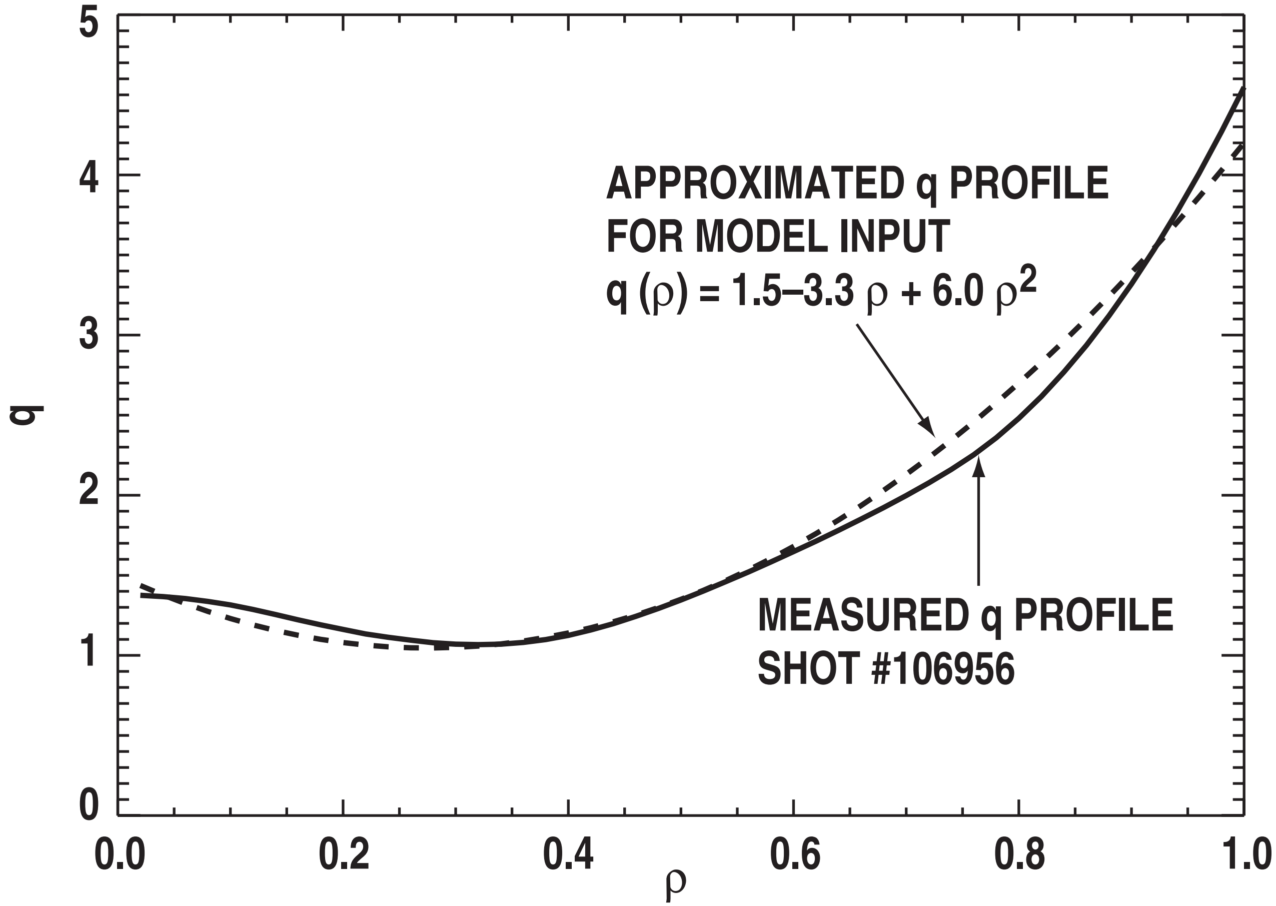
- Since $\mathcal{T}_H$ or $\mathcal{T}_L \propto P_o^{-1/2}$ and $\mathcal{T}_{neo} \propto P_o^1$, it may not be much a surprise that the combining effect produces a parameter space for the confinement to stay rather insensitive to the input power.

- The confinement appears to improve more than linearly with I_p. Since $\mathcal{T}_L \propto I_p^{4/5}$ and $\mathcal{T}_{neo} \propto I_p^3$, the trend appears to show the combining effect.

- It is interesting to see that the confinement degrades slowly with density for the high density range, not so severely as the case with neoclassical scaling. In general, it appears that the presence of outer L-mode or H-mode plasma layer softens the extreme swings of the neoclassical scaling.

- Based on the model analyses, Shot# 106956 appears to be close to the optimal point for operation since the confinement time would not improve much with higher levels of P_{in} and n_p. And an increase in I_p may not be possible due to the reverse shear requirement to the q profile.

q PROFILE FOR MODEL INPUT



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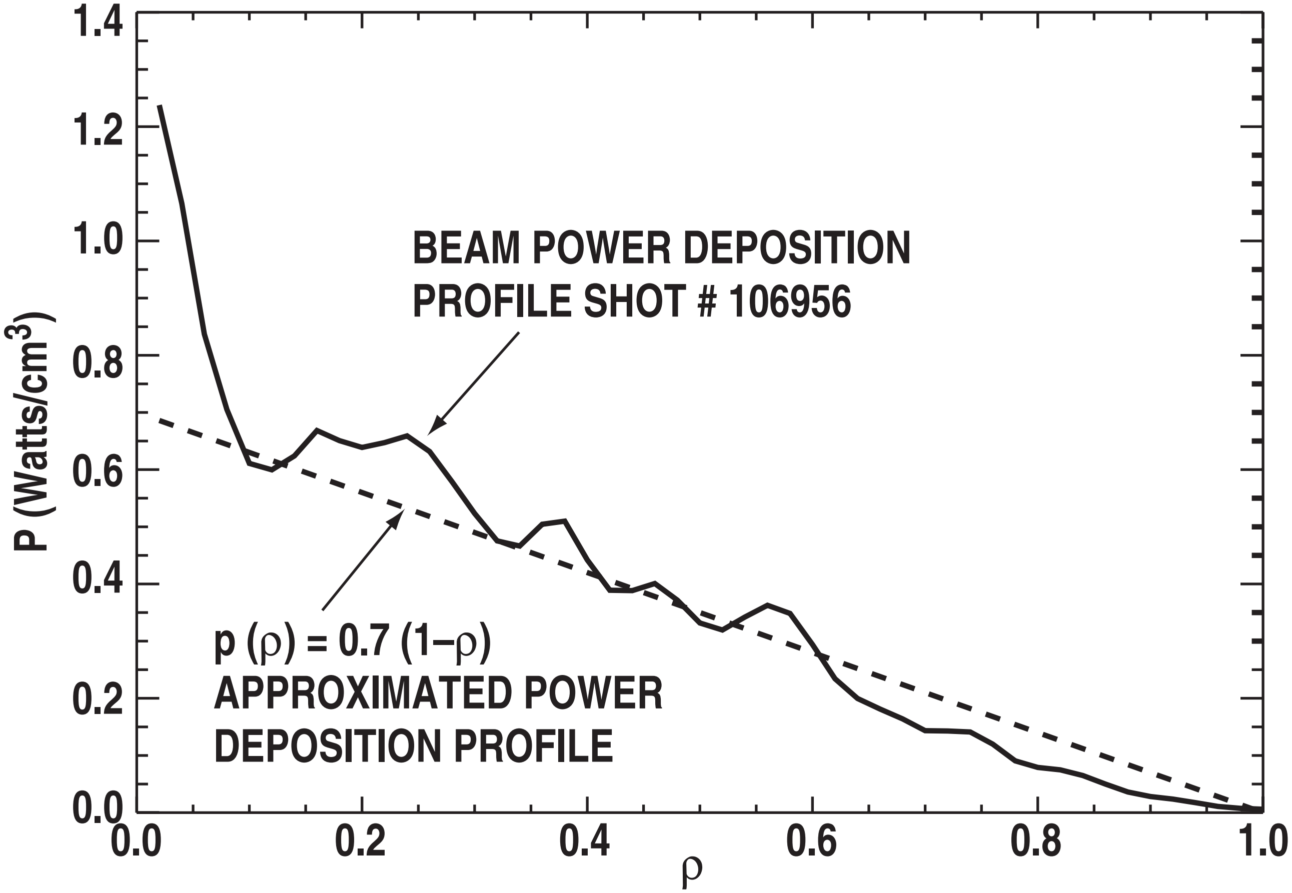
POWER DEPOSITION PROFILE FOR MODEL INPUT



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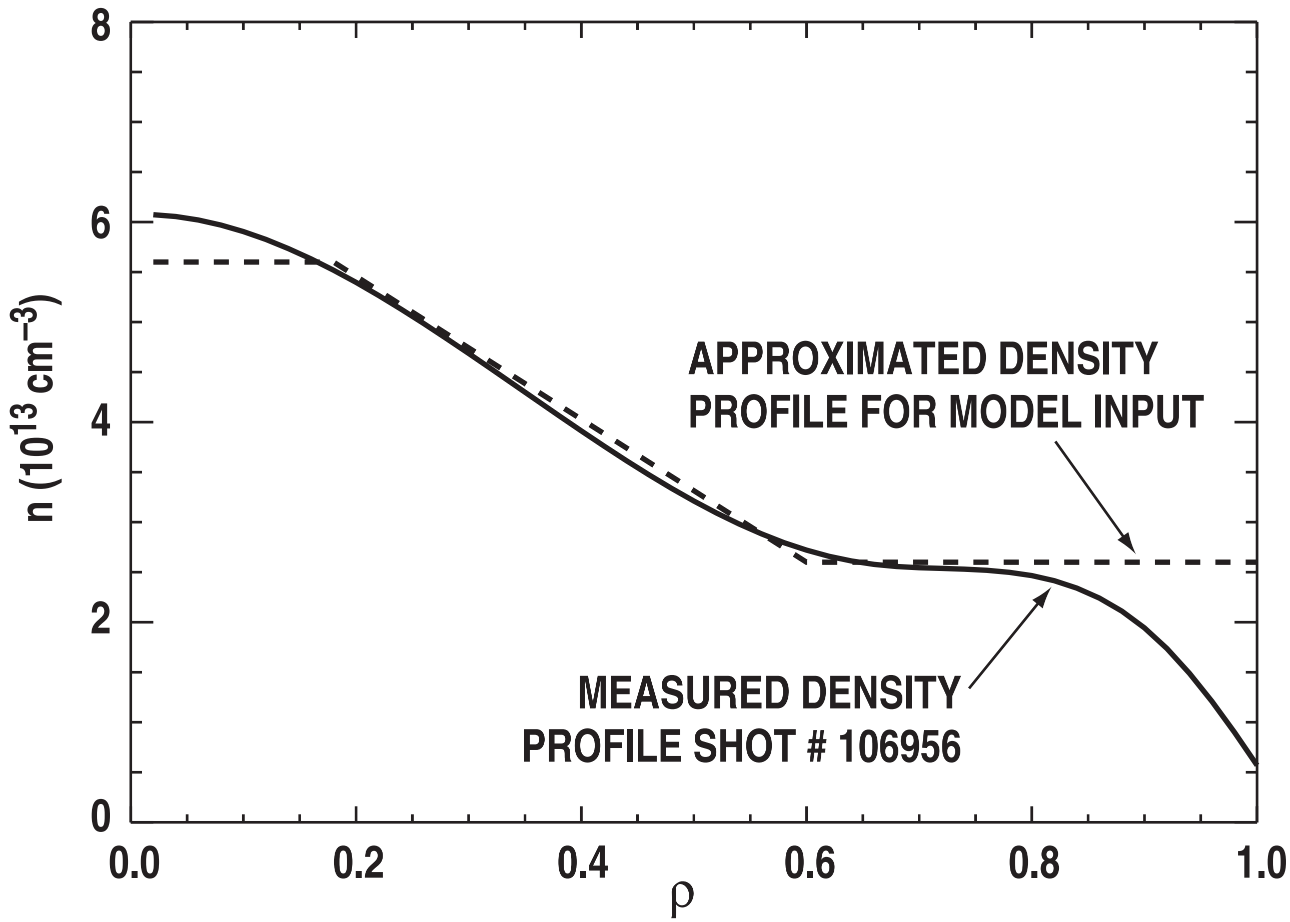
DENSITY PROFILE FOR MODEL INPUT



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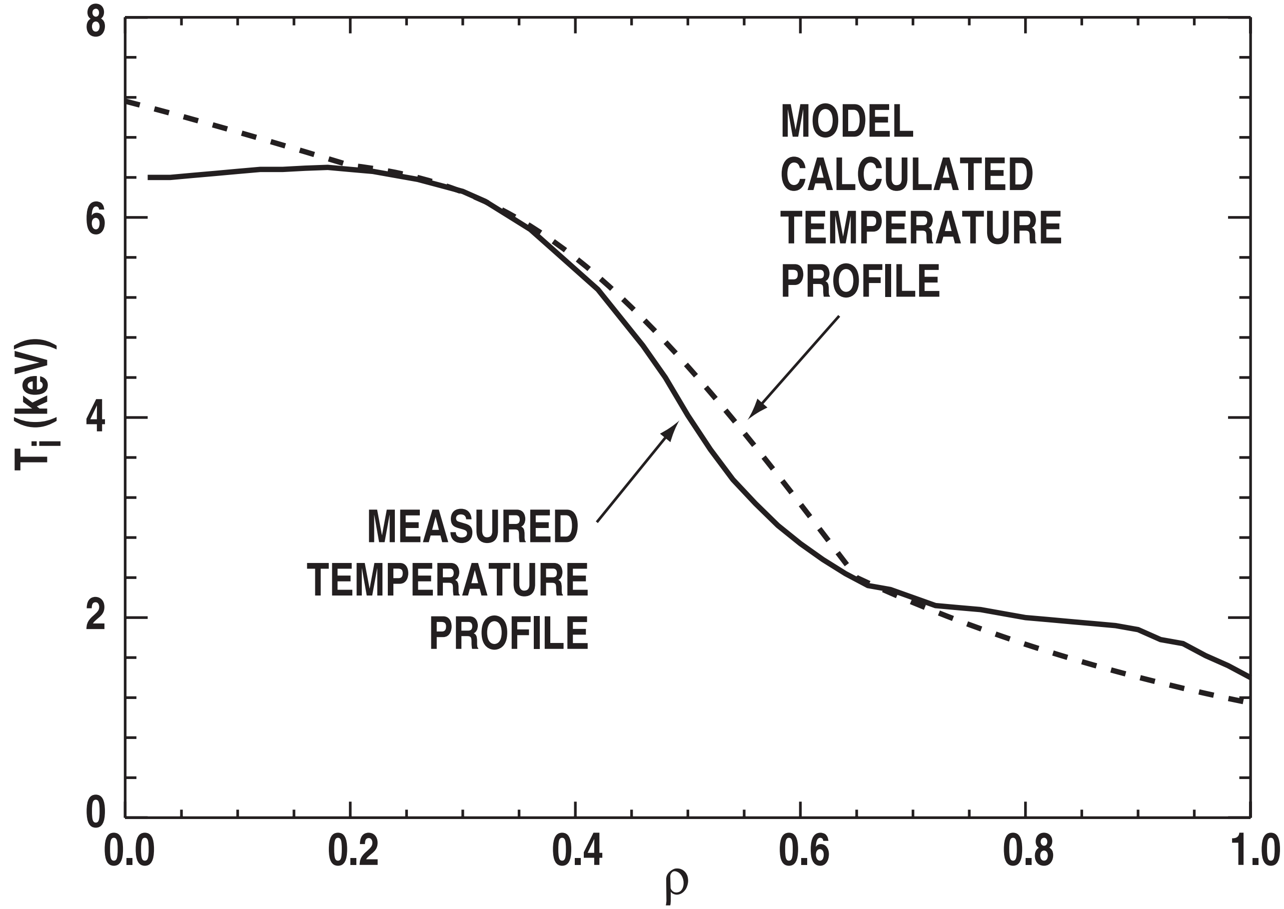
ITB CONFINEMENT SCALING MODEL



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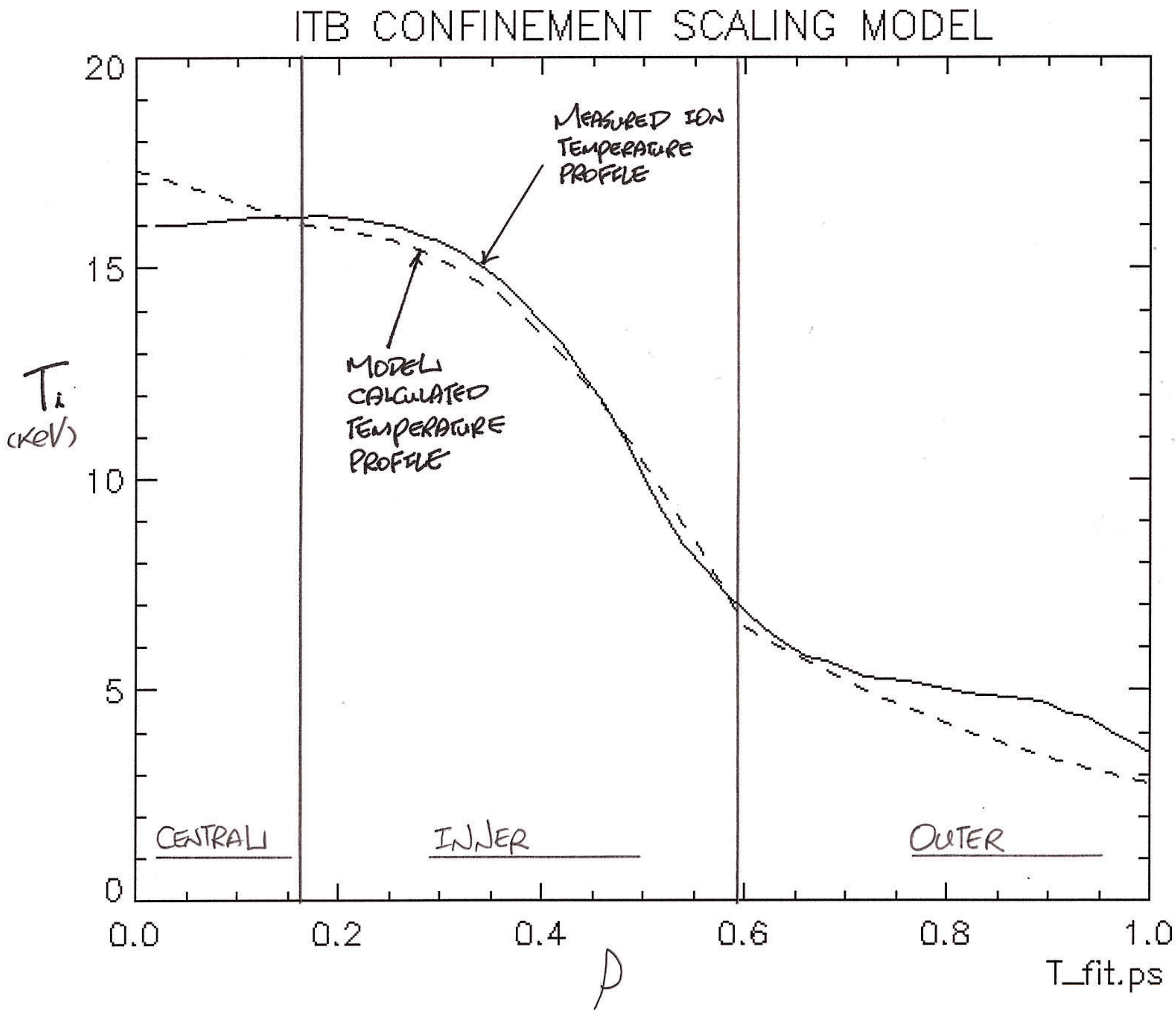
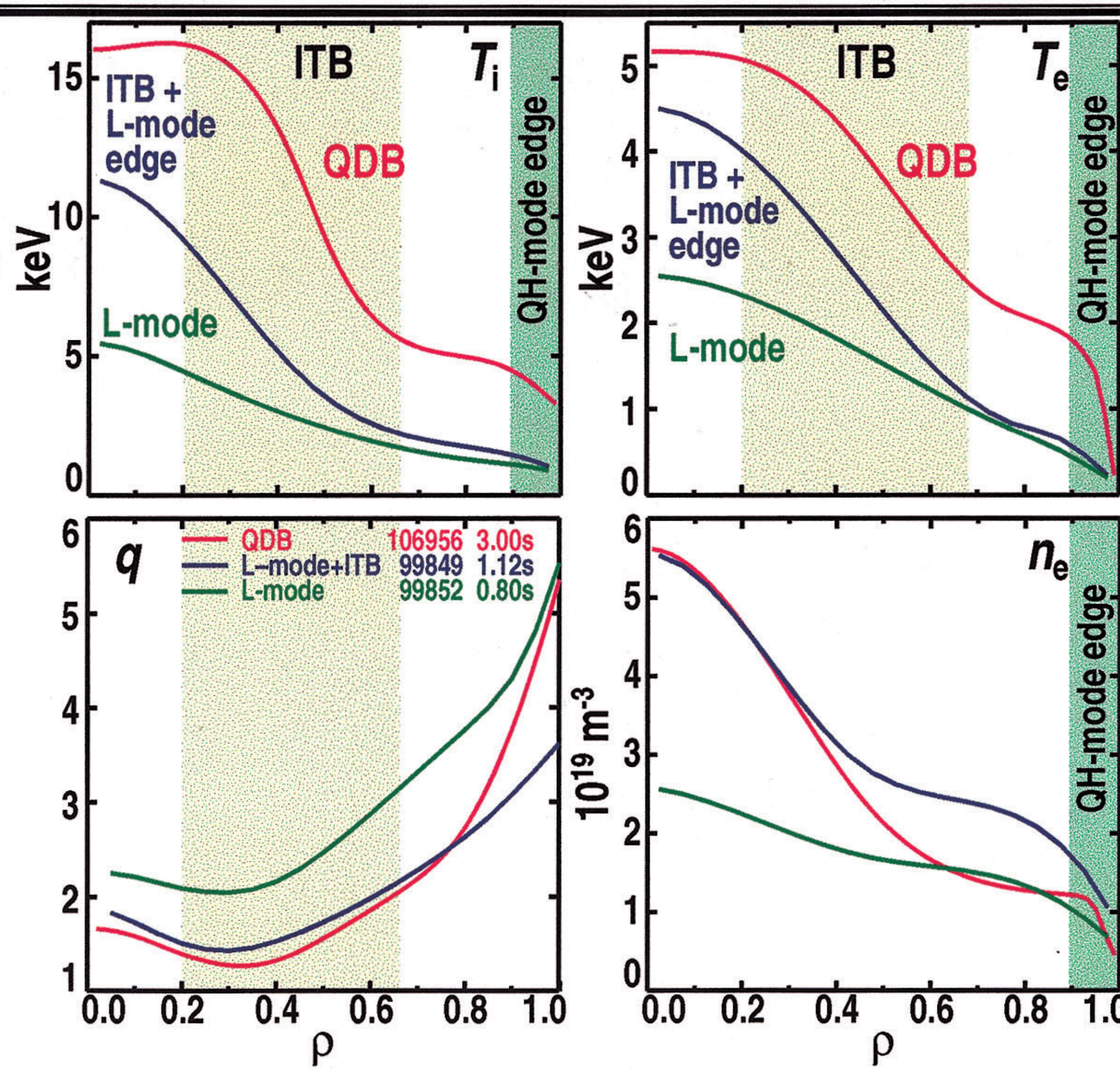

ITB CONFINEMENT SCALING MODEL
MEASURED ION TEMPERATURE PROFILE
MODEL CALCULATED TEMPERATURE PROFILE
T_i (keV)
CENTRAL
INNER
OUTER
0
5
10
15
20
0.0
0.2
0.4
0.6
0.8
1.0
ρ
T_fit.ps

QDB REGIME COMBINES CORE TRANSPORT BARRIER WITH QUIESCENT EDGE BARRIER — "QUIESCENT DOUBLE BARRIER"

- Edge pedestal elevates central temperatures, improving fusion performance



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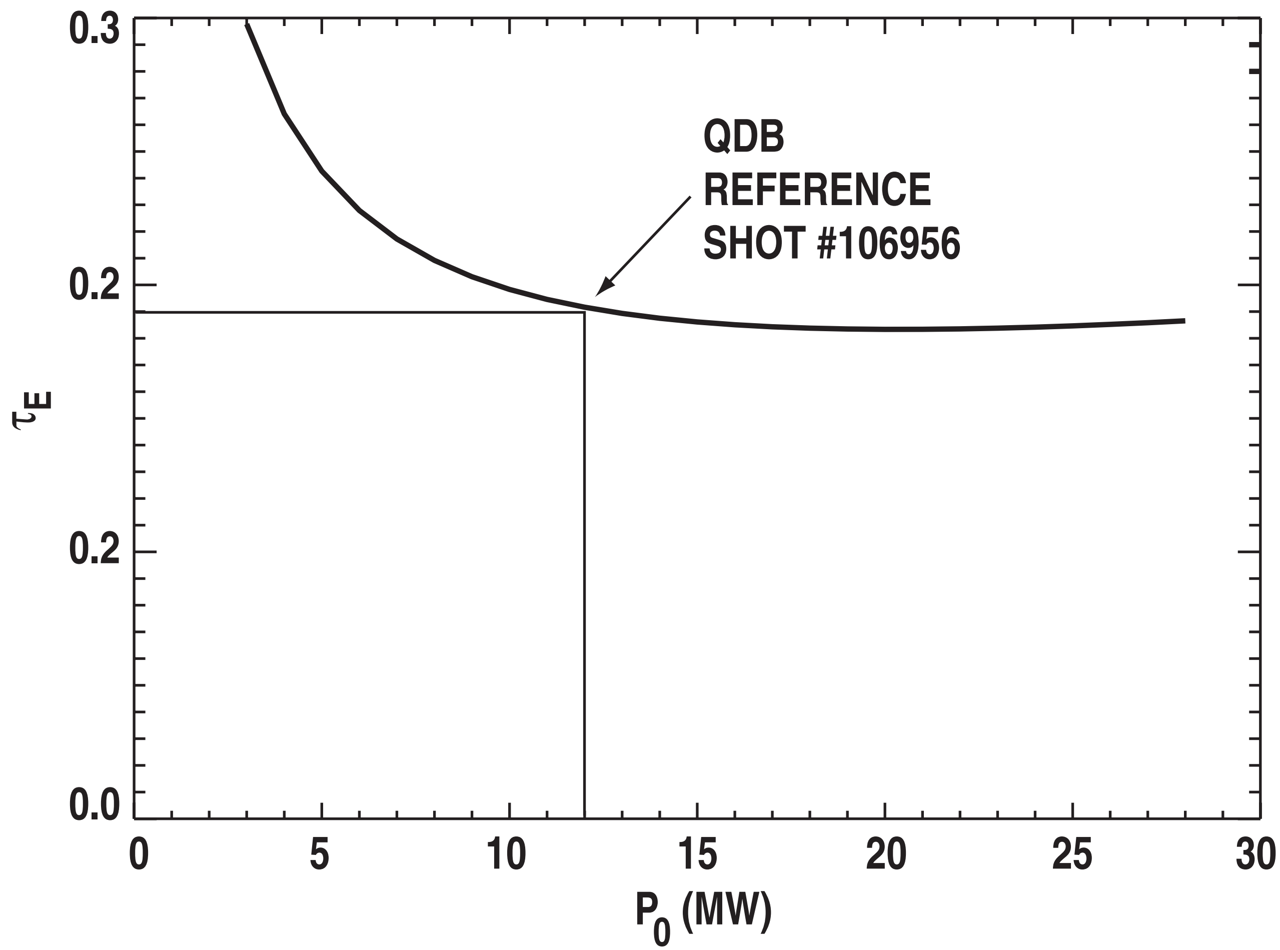
ITB CONFINEMENT SCALING MODEL



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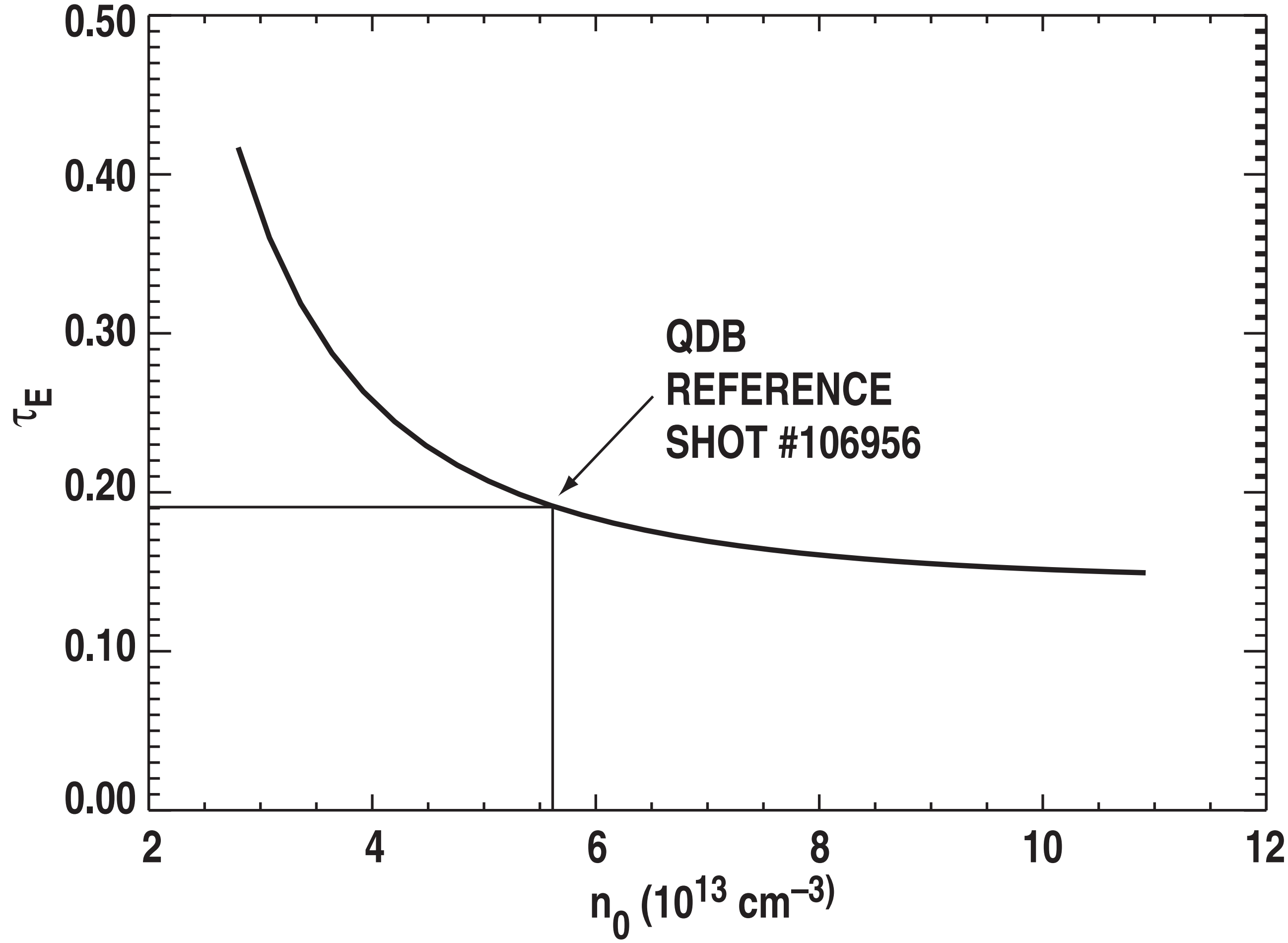

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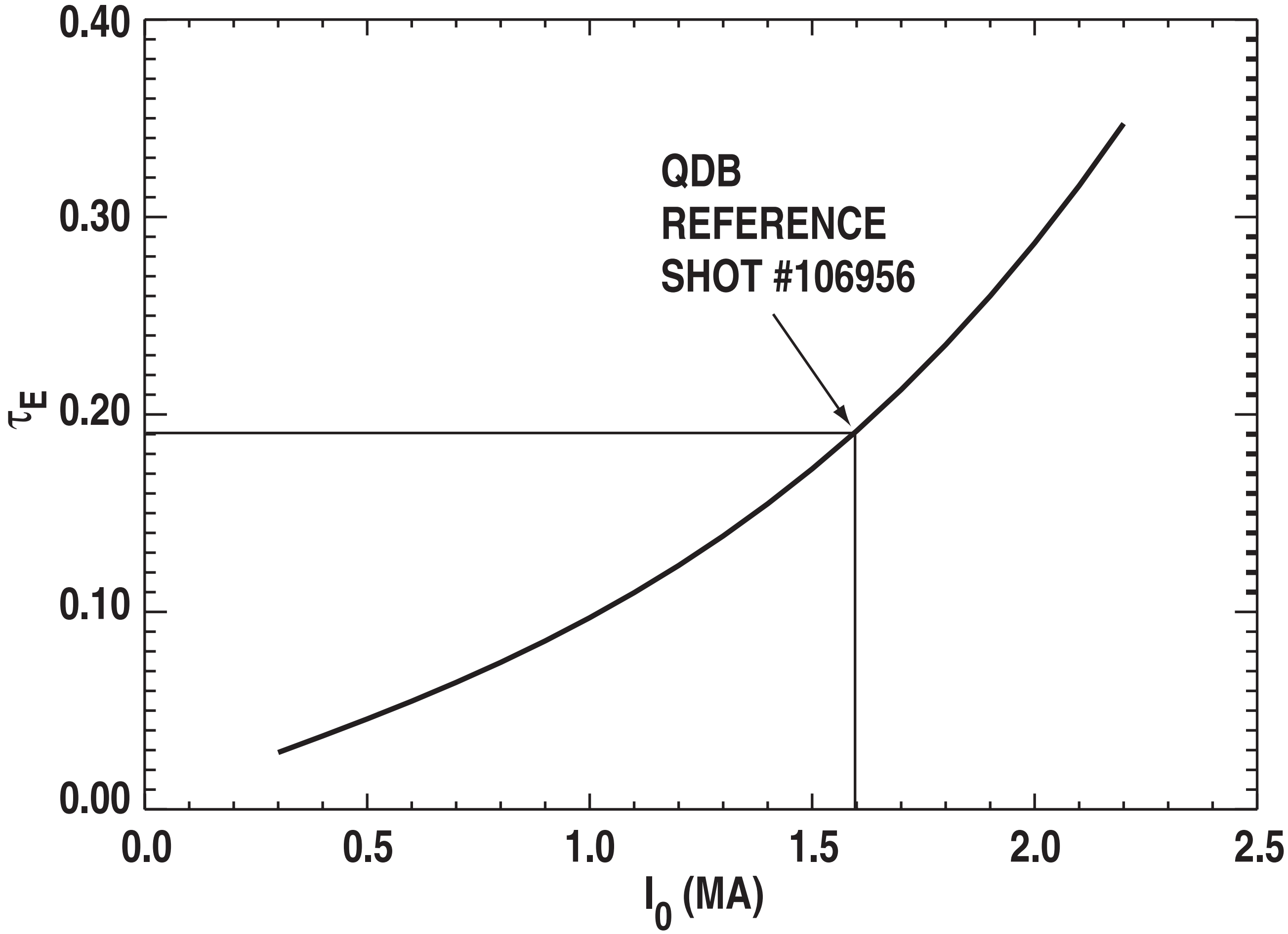
ITB CONFINEMENT SCALING MODEL



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V. SUMMARY

- In order to study the confinement scaling of a plasma with internal transport barrier, we developed a model which divides the plasma into three regions:
  - The outer L or H region,
  - The ITB region,
  - The central L or H region.

- χ_{neo} is assigned to the ITB region.

  χ_L, obtained based on experimental observations, for the L-mode region.

  $\chi_H = \chi_L$, the H-mode and L-mode have the same heat transport process but different plasma boundary conditions.

- The model is made sufficiently simple so analytic solutions are obtained for the temperature profile and the global energy confinement time.

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- The model analyses is based on using an experimental QDB shot (shot #106956) as the model input. The measured ion temperature profile helps to determine the constant in the individual diffusivity expression.

- The model result shows that the confinement may not degrade with input power for above a certain input power level. The feature is different from that of L-mode and H-mode plasmas. The change appears to come from the neoclassical transport assumed for the ITB region.

- The confinement appears to improve more than linearly with the plasma current. It appears that the less than linear scaling of L- and H-mode gets pulled up by the more than linear scaling of the neoclassical transport assumed for the ITB region.

- The model demonstrates that the global energy confinement is a combined result from the H (or L) region and the neoclassical region. The distinctive features reflect not only the individual diffusivities but also the complex relationships in between the regions. In the end, ITB improves the overall confinement over the H-mode scaling. And the outer region of H-mode plasma helps to soften the extreme swing of neoclassical scaling.