EUROPEAN FUSION DEVELOPMENT AGREEMENT

# Particle and Energy Transport in Dedicated $\rho^*$, $\beta$ and $\nu^*$ Scans in JET ELMy H-modes

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## Structure of talk:

- Background
- Energy transport results
  - $\rho^*$, $\beta$, $\nu^*$ scans
- Trace tritium transport results
  - $\rho^*$, $\beta$, $\nu^*$ scans
- Theory and modelling implications
- Predictions for ITER

# Background

- **Kadomtsev (SJPP, 1975)** and **Connor and Taylor (NF, 1977)** showed

$$\omega_c \tau_E \propto B\tau_E \propto F(\rho^*, \beta, \nu^*)$$

$\rho^*$= dimensionless Larmor radius, $\beta$= kinetic to magnetic pressure ratio, $\nu^*$=normalised collisionality.

- IPB98(y,2) scaling from the Multi-machine database has dimensionless form

$$B\tau_E \propto \rho^{*-2.70}\, \beta^{-0.9} \nu^{*-0.01}$$

- 2-point scans of $\rho^*$, $\beta$ and $\nu^*$ on JET (and JET/DIII-D for $\beta$) in 1996 gave

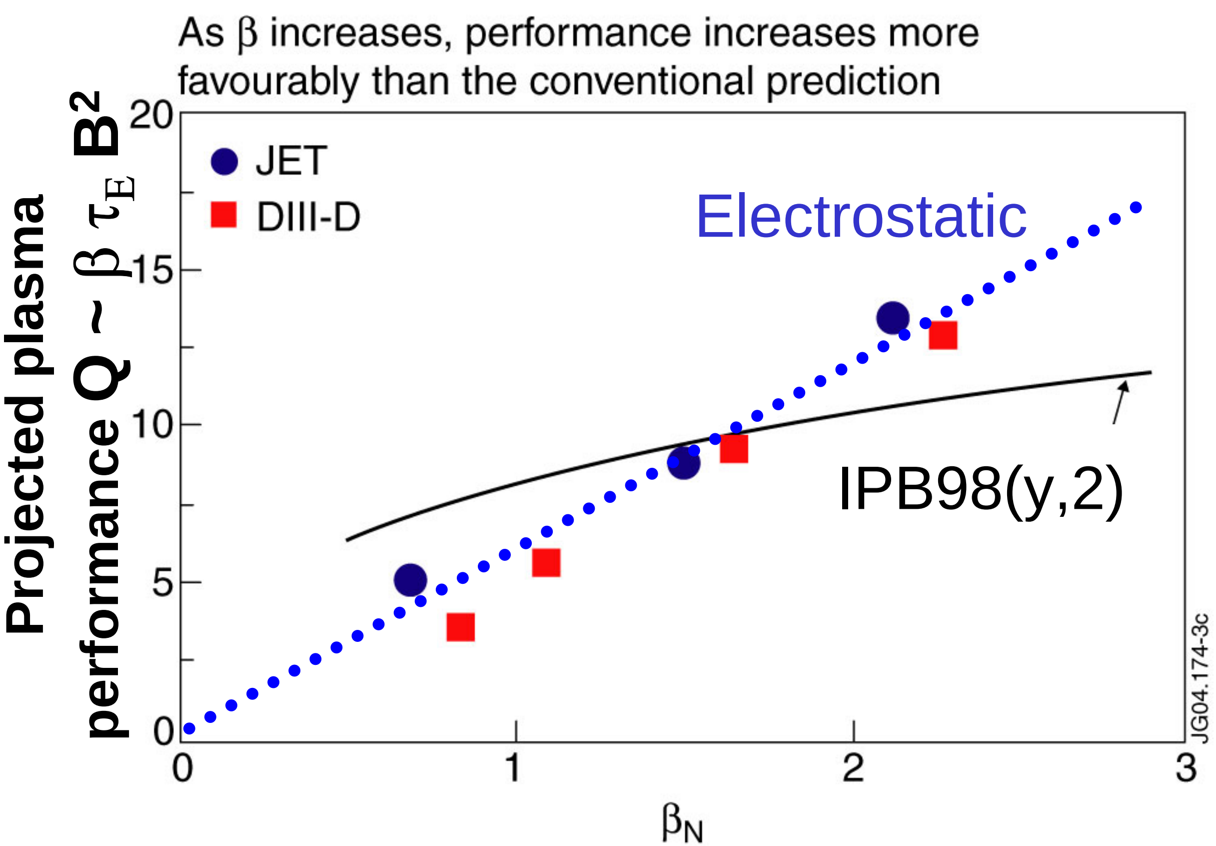
$$B\tau_E \propto \rho^{*-3.0}\, \beta^{-0.0} \nu^{*-0.3}$$

- Particle transport is less well studied, He experiments indicate

$$\tau_{p,He} = 5 \times \tau_E$$

# Energy: β scan results

- Extensive β scans (ρ*, β and **q** fixed) by JET and DIII-D in 2003 [**D C McDonald *et al* (PPCF, 2004) and C C Petty *et al* (PoP, 2004)**]
- $B\tau_E$ had only a weak dependence on β, even within Type I ELMs

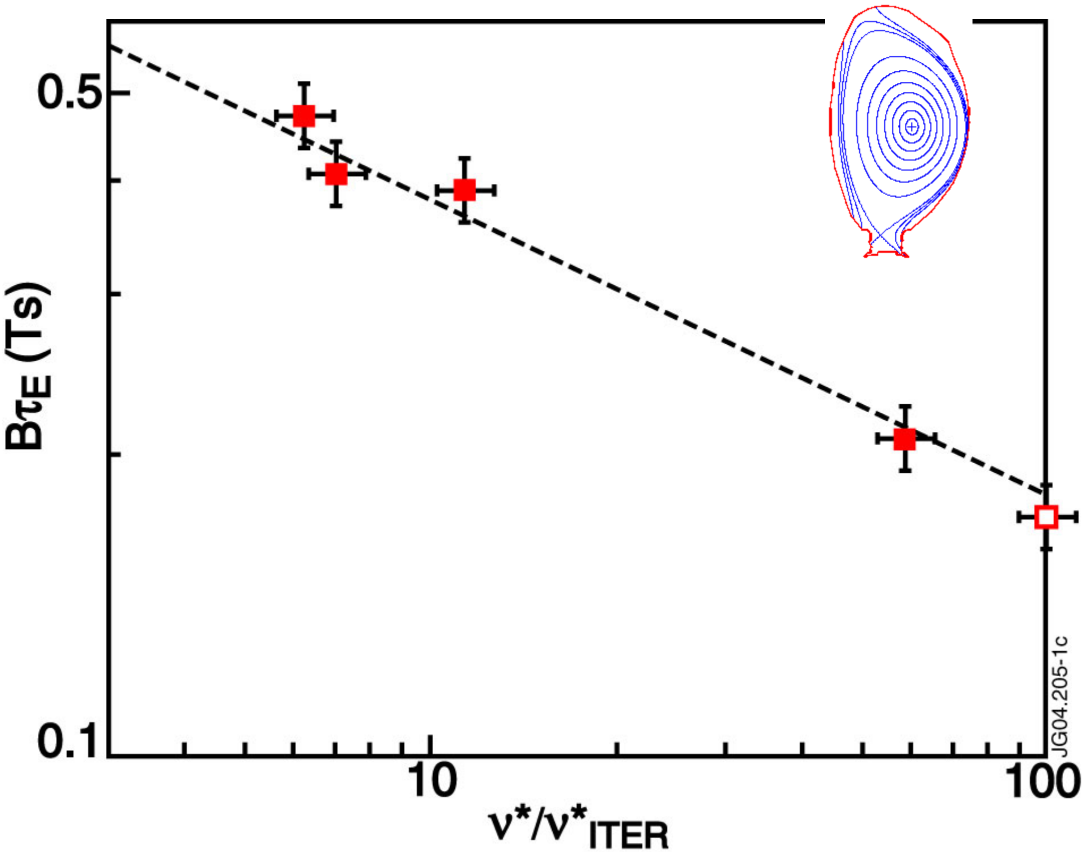



$$B\tau_E \propto \beta^{0.0\pm0.1}$$

- Hence, provided steady stable high β operation can be maintained the performance of ITER will be significantly improved

# Energy: $\nu^*$ scaling

- Part of a collaboration with CMOD, so a high triangularity shape was used
- The current was varied in the range $\mathbf{I_p = 0.68 - 1.17MA}$
- To keep $\rho^*$, $\beta$ and **q** fixed: $\mathbf{B \propto I;\ n \propto I^0;\ T \propto I^2}$



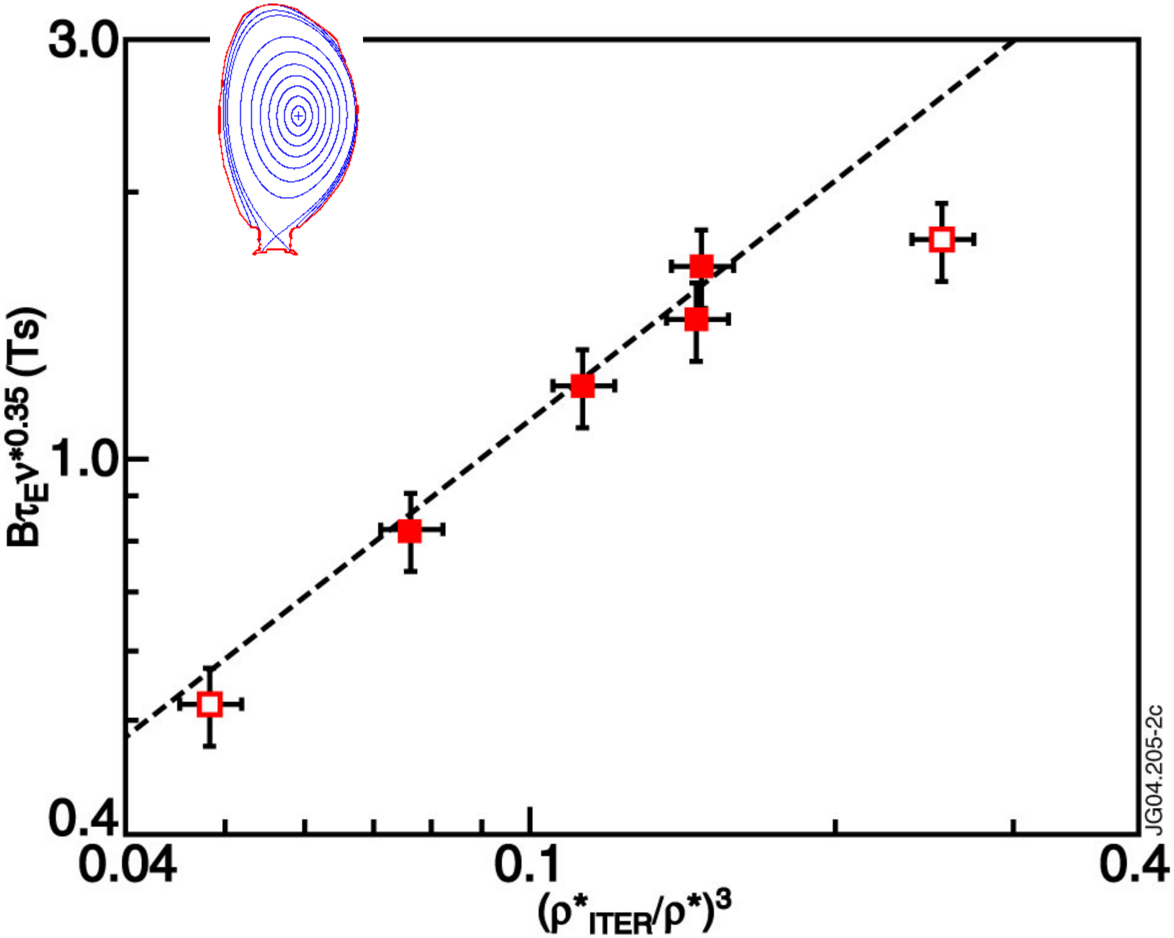

$$B\tau_E \propto \nu^{*\,-0.35\pm0.04}$$

**RMSE = 6%**

Similar to 2 point scan of 1996 ($B\tau_E \propto \nu^{*\,-0.28}$)

# Energy: ρ* scaling with Type III ELMs

- Low triangularity shape. Current varied in the range **$I_p$ = 1.3 - 4.3MA**
- To keep β, ν* and **q** fixed: **B ∝ I; n ∝ $I^{4/3}$; T ∝ $I^{2/3}$**



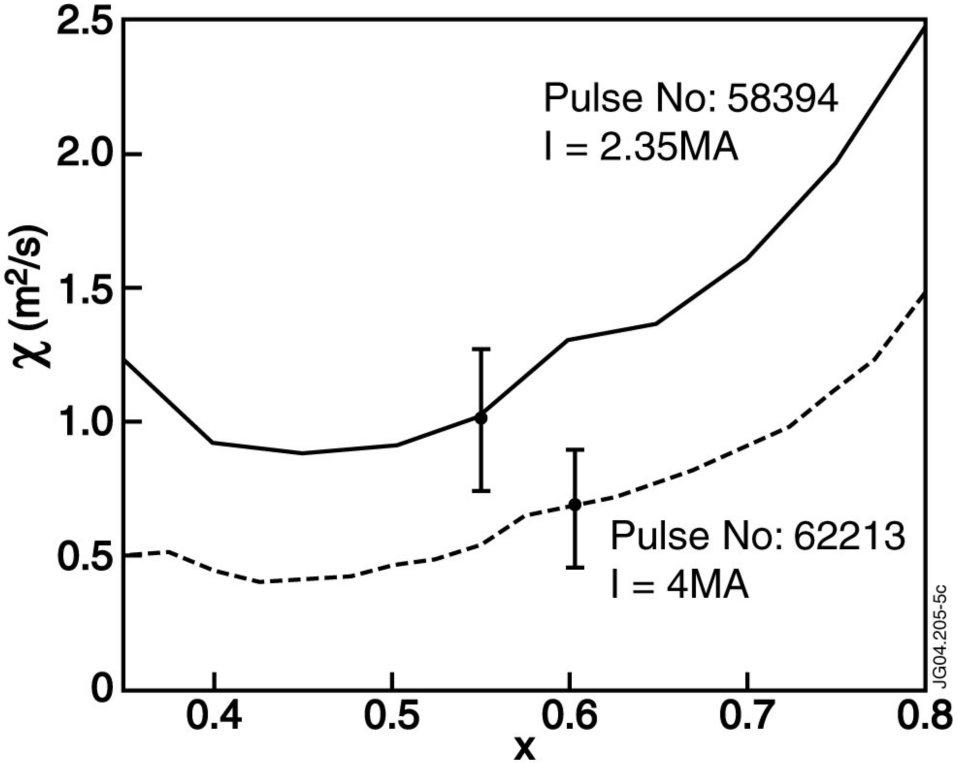

$$B\tau_E \propto \rho^{*-2.9\pm0.5}$$

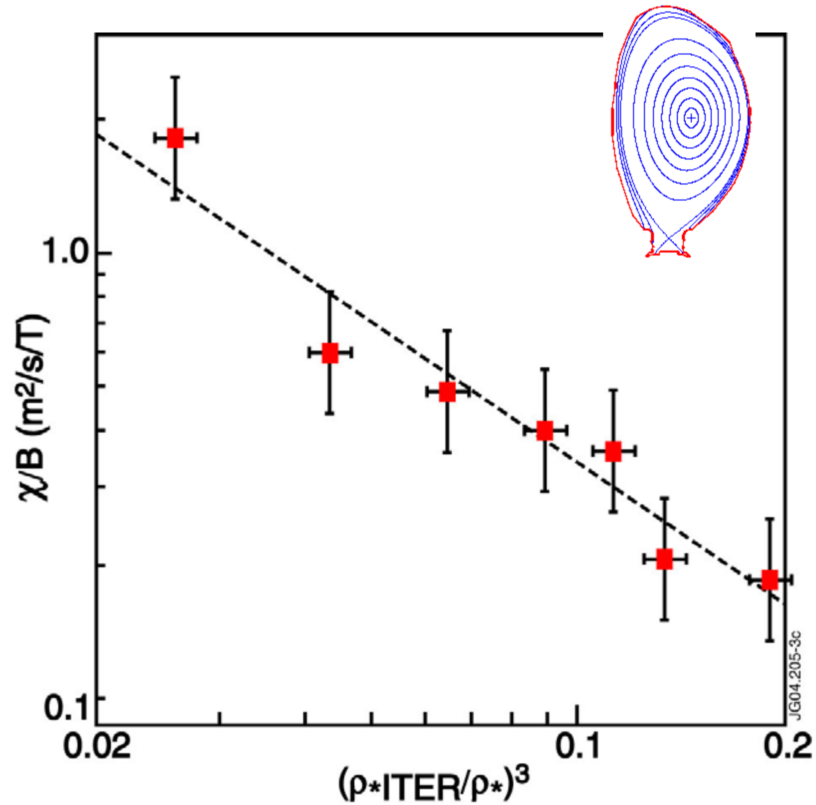
**close to gyro-Bohm**

- The ν* and β match was not perfect for the extremes (open points)
- introducing a $\nu^{*0.35}$ brings them closer to the scaling

# Energy: ρ* scan with Type I ELMs

- So for the full scan, **Ip = 1.4 - 4MA**, we take χ's at **x = 0.5**



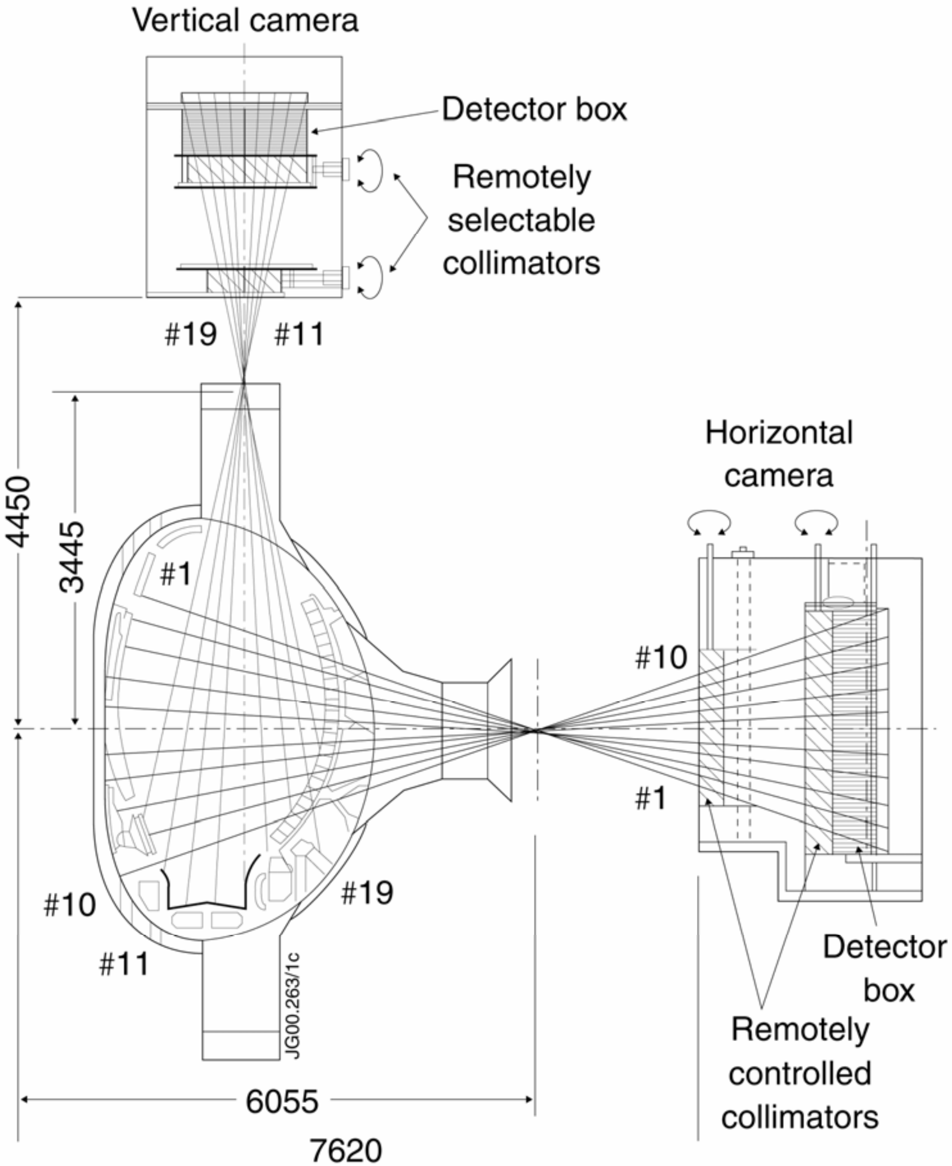

- compare thermal diffusivities

- Here $\chi \propto$ **1 / B**, consistent with a gyro-Bohm scaling

$$\chi/\mathbf{B} \propto \rho^{*+3.2\pm0.4}$$

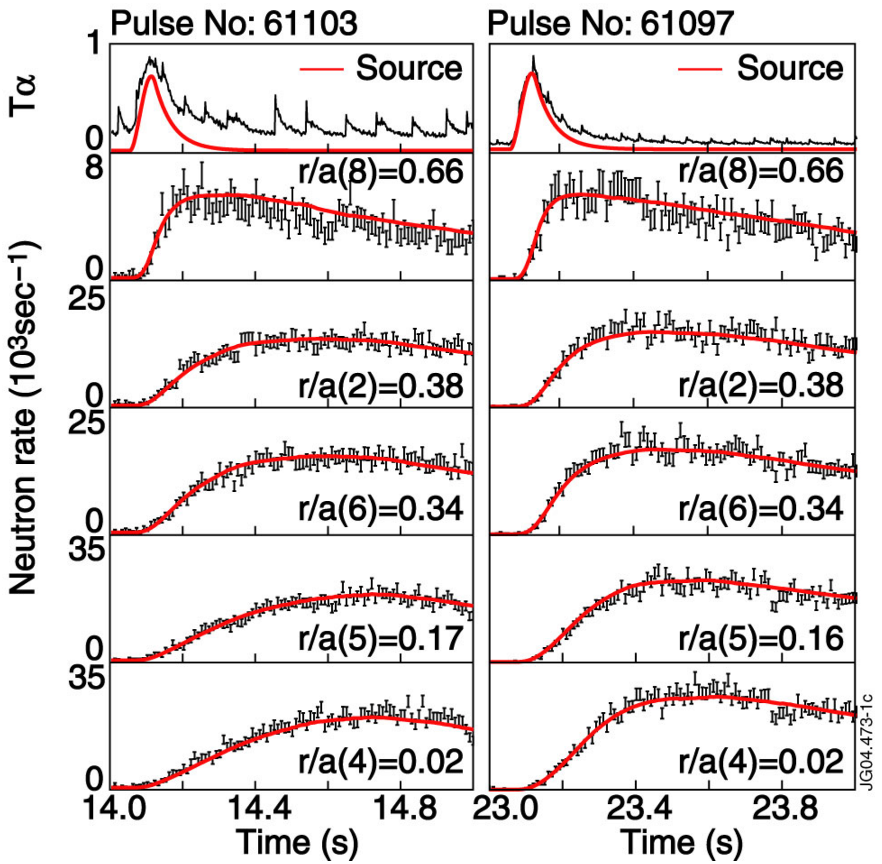
**again, close to gyro-Bohm**

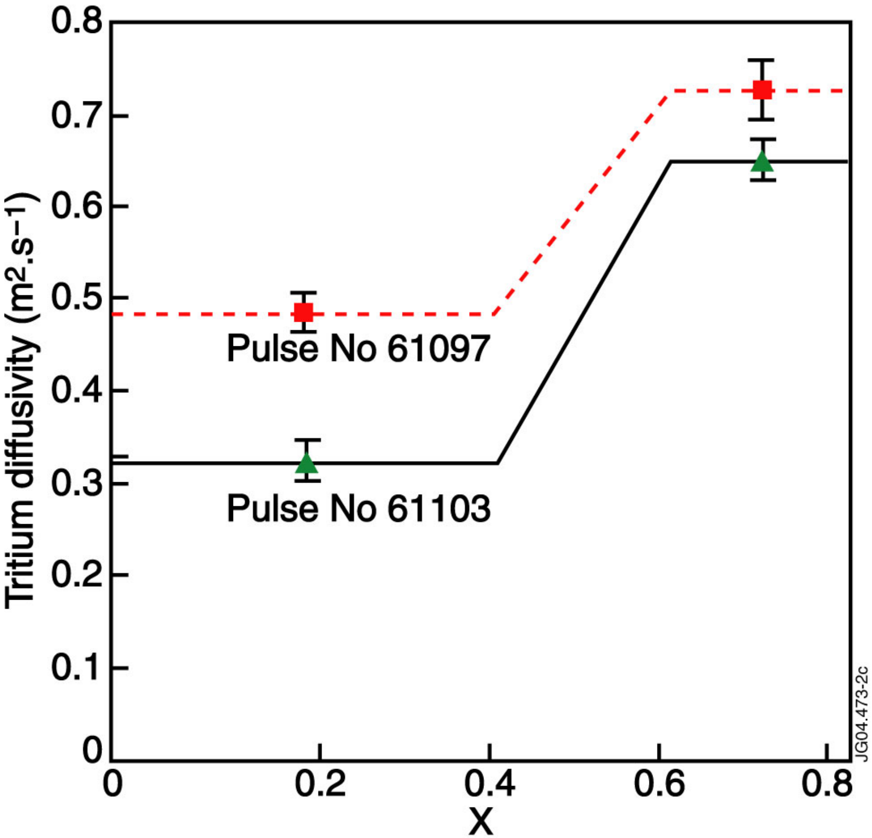
# Trace tritium: non-dimensional (ρ*, β, ν*) experiments




- Set of **5** discharges prepared in D-D
  - **3** point **ρ*** scan
  - **2** point β scan
  - **2** point **ν*** scan
- Reran with a T puff (**2.5-5mg** over **80ms**)
- Line integrated D-T and D-D neutrons measured with 10 horizontal and 9 vertical cameras

# Trace tritium: fitting diffusivity and advection



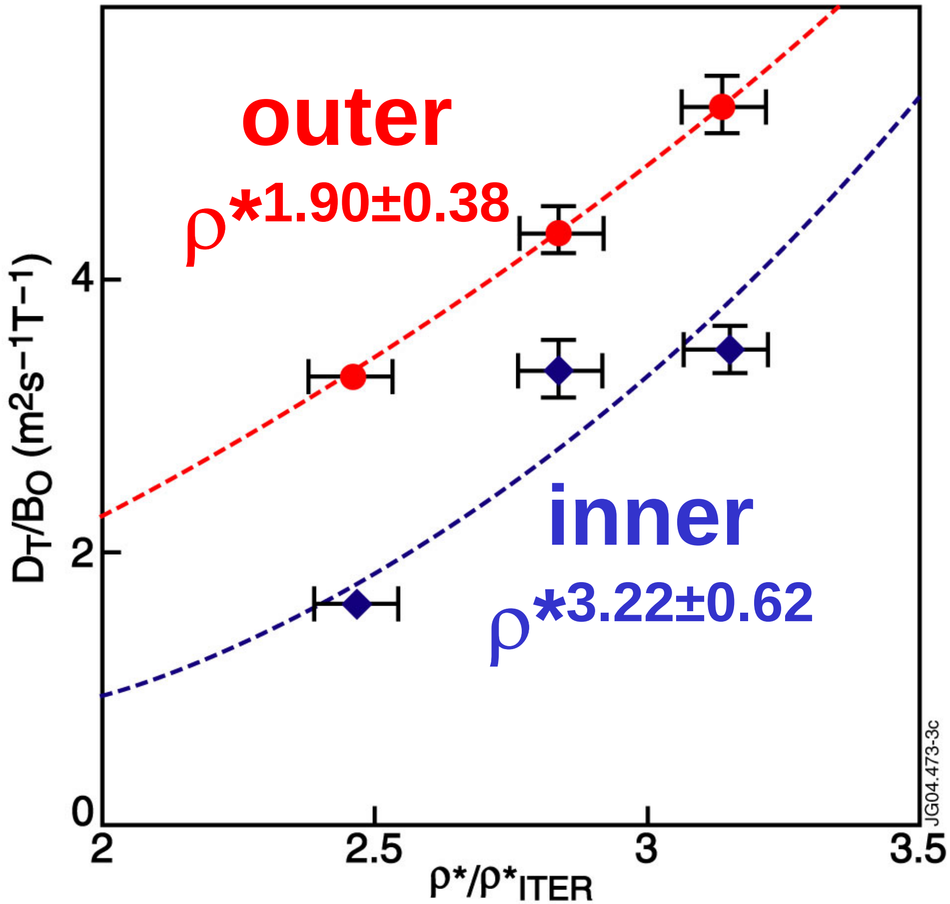




- Take **V** + **D** with 3 basis functions each
- SANCO forward models $\mathbf{n_T}$ + neutrons
- UTC finds best fit with error bars

$$\frac{\partial n_T}{\partial t} = \nabla \bullet \left( n_T \mathbf{v} - D \nabla n_T \right) + s$$

# Trace tritium: ρ* scan in Type I ELMs

- Low triangularity shape. Current varied in the range **$I_p$ = 2 - 2.75MA**
- 3 point scan with inner (**x=0-0.45**) and outer (**x=0.65-0.85**) measurements




$$D_{inner}/B_0 \propto \rho^{*3.22\pm0.62}$$

- **gyro-Bohm like behaviour**

$$D_{outer}/B_0 \propto \rho^{*1.90\pm0.38}$$

- **Bohm like behaviour**

- Both results are consistent with the 1997 discharges

# Trace tritium: β and ν* scan results

- Two point β scan

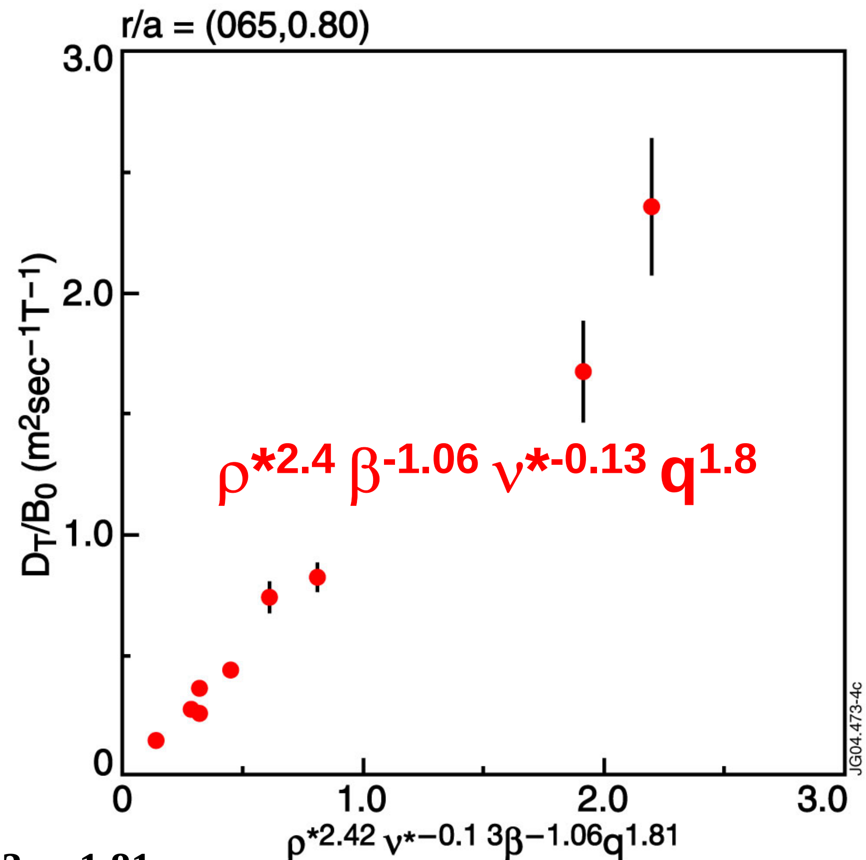
$$D_{inner} \propto D_{g-Bohm} \beta^{-0.34\pm0.08}$$

$$D_{outer} \propto D_{Bohm} \beta^{-0.55\pm0.09}$$

- Two point ν* scan

$$D_{inner}/B_0 \propto \nu^{*-0.51\pm0.17}$$

$$D_{outer}/B_0 \propto \nu^{*-0.40\pm0.15}$$




- Fit to outer data for **9** shots gives

$$D_{ELMy}/B_0 \propto \rho^{*2.4}\ \beta^{-1.06} \nu^{*-0.13}\ q^{1.81}$$

- The ν* results is more ambiguous, but β ↑ » $D_T$ ↓ » $\tau_T$ ↑

- Across whole database $\boxed{D_T/\chi=0.3\text{-}1.5}$

# Summary of experimental results

- The ρ*, β and ν* results for thermal transport may be summarised as

$$B\tau_E \propto \rho^{*\,-3.1\pm0.5}\,\beta^{0.0\pm0.1}\,\nu^{*\,-0.35\pm0.05}$$

***gyro-Bohm*** ***Electrostatic*** ***- Collisional***

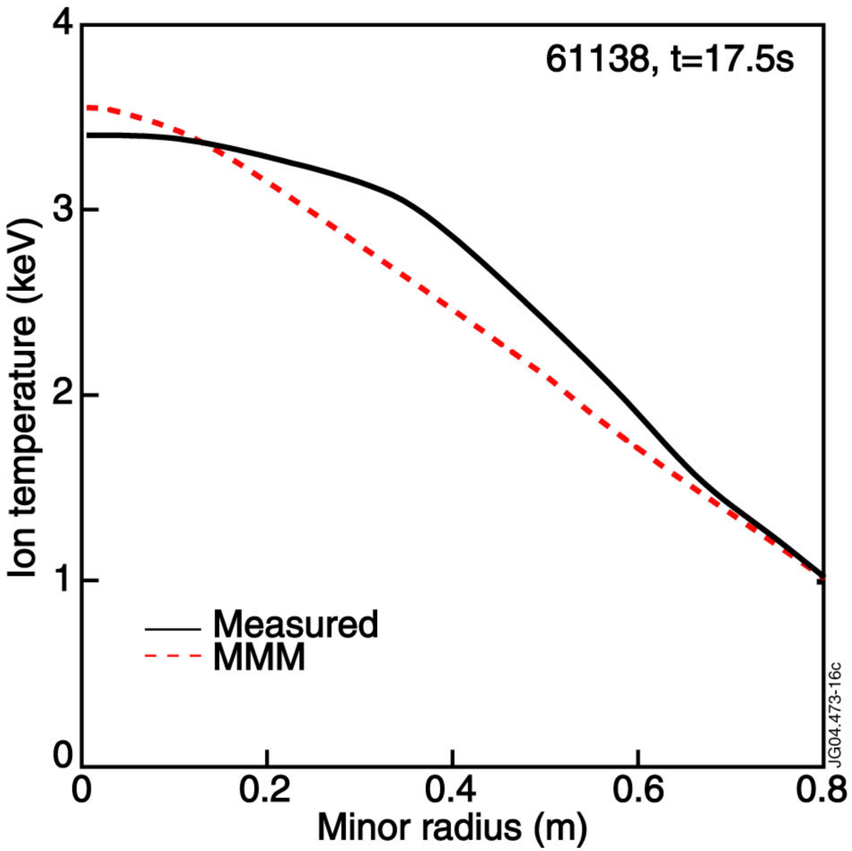
- The ρ*, β and ν* results for trace T transport may be summarised as

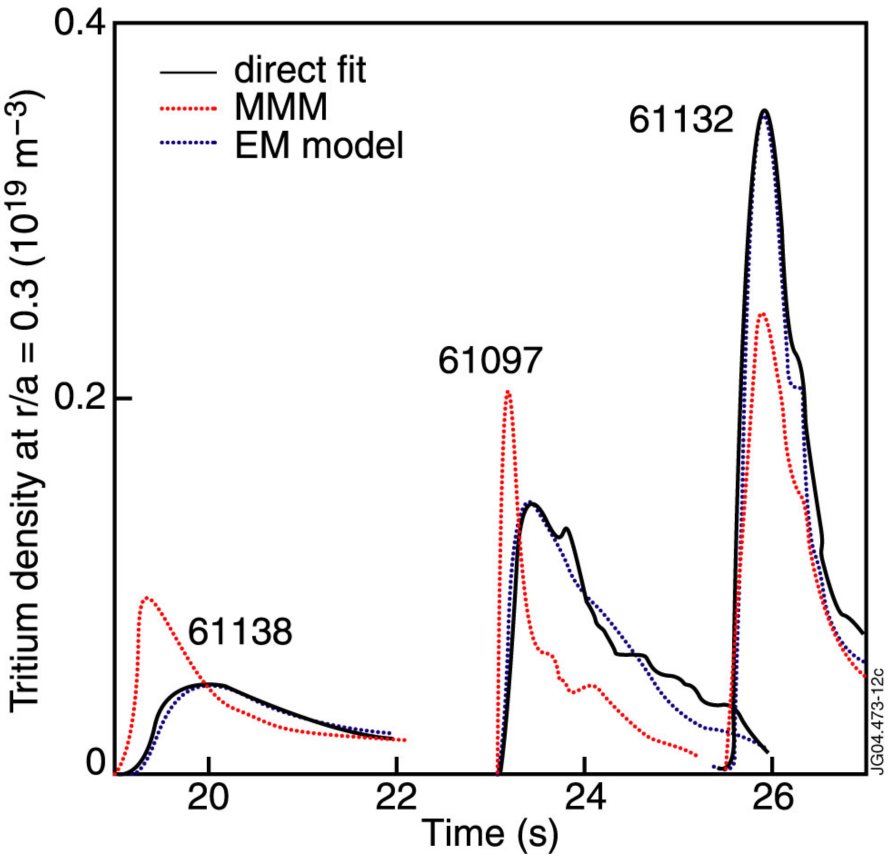
$$B/D_T \propto \rho^{*\,-3.2\pm0.62}\,\beta^{+0.5\pm0.1}\,\nu^{*\,+0.5\pm0.1}$$

***gyro-Bohm*** ***Electromagnetic*** ***+ Collisional***

- With a weaker, Bohm like ρ* scaling in the outer region **x=0.65-0.85**
- Positive effect of β on trace T confinement. Similar behaviour seen for trace helium [**C C Petty *et al* (2004)**]

# Transport modelling for trace tritium discharges



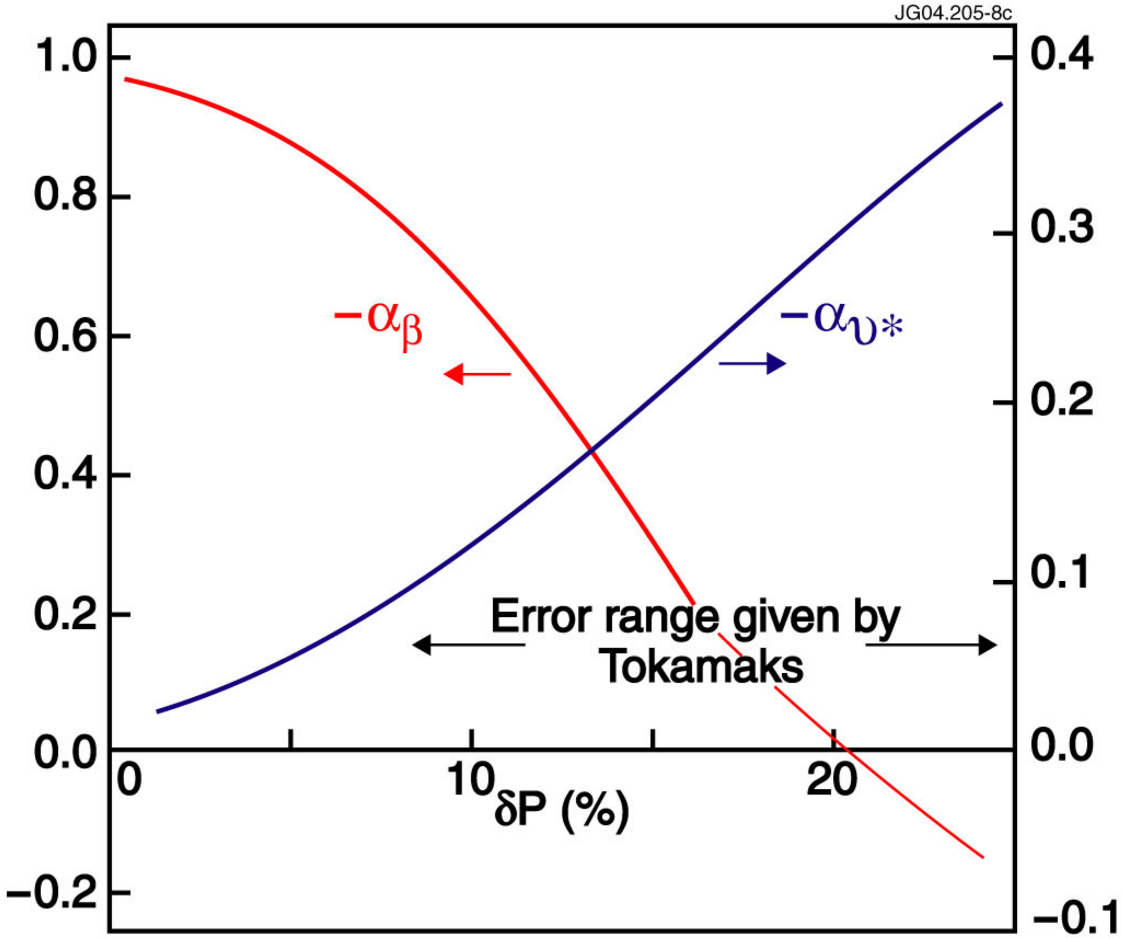




- gyro-Bohm like, ES bhvr. of thermal transport shots well described by ES models like MMM

- non ES bhvr. of trace T transport requires a EM model
- A model based on neo-classical orbits in stochastic EM fields fits with the data

# Re-analysis of the Multi-machine Database

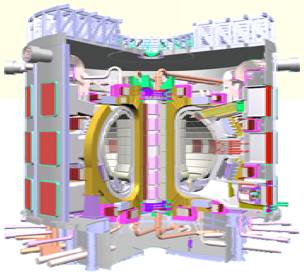
- PCA “Errors in variables methods” now being used to determine scaling

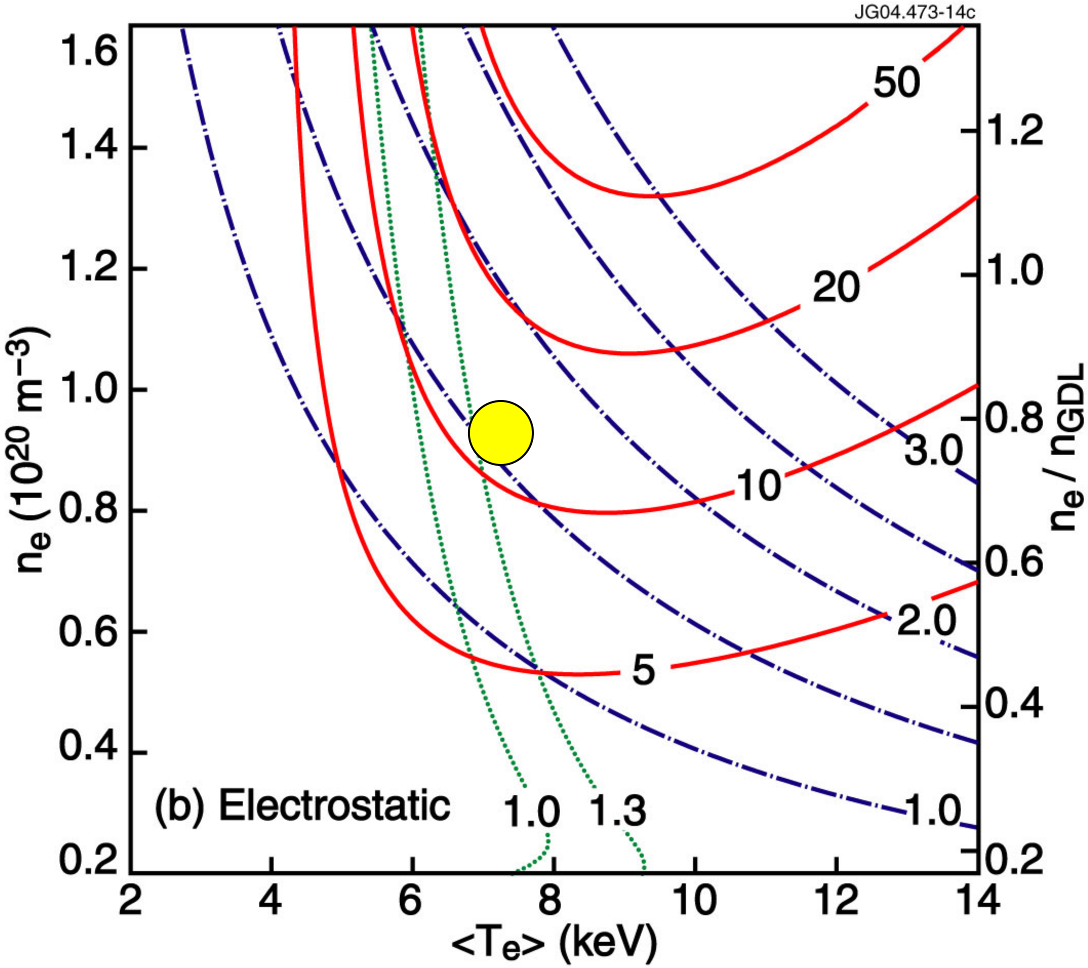



- $\beta$ dependence found to be strongly dependent on errors in **P** and **W**
- The exponent of $\beta$, $\alpha_\beta$, lies in the range **-0.7 < $\alpha_\beta$ < 0**
- $\nu$* correlates with $\beta$ dependence

**See Cordey *et al*, P3-32**

# Consequences for ITER






- For ES model,at operating point, **+2% $\tau_E$** at **$\beta_N$ = 1.8**
- However, scaling gives **+50% $\tau_E$** at **$\beta_N$ = 3.0**
- Other ES models give even higher $\tau_E$
- POPCON plots show access to very high **Q** for $\beta_N$ **= 3.0**
- Impact of higher particle confinement, particularly for He ash, at $\beta_N$ **= 3.0** remains to be assessed

# Summary of theory and modelling implications

- results of scans

$$B\tau_E \propto \rho^{*-3.1}\,\beta^{-0.0}\,\nu^{*-0.35}$$

$$B/D_T \propto \rho^{*-3.2}\,\beta^{+0.5}\,\nu^{*+0.5}$$

- ES, g-Bohm
- EM, g-Bohm

- ES models, such as MMM, describe energy confinement
- Particle model based on neo-classical transport in stochastic EM fields does describe the EM beta dependence
- Candidates exist (ITG...), but describing the different particle/energy transport ($\beta$ and **$D_T/\chi$=0.3-1.5**) in one model remains a challenge for theory.
- Improvement in the predicted $\tau_E$ for ITER would be substantial at $\beta_N$**≥3.0**. Particle effects to be assessed.