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# ABSTRACT

There is emerging evidence that the variation in the measured beta dependence of energy confinement in H-mode plasmas is due in part to different turbulent modes being dominant, with ion temperature gradient (ITG) modes being important in weak beta scaling cases and micro-tearing modes being potential candidates explaining strong beta degradation. This points out the need to determine whether micro-tearing modes are expected to appear in ITER. Another factor is that the normalized H-mode pedestal height may not be constant over a beta scan, which affects core transport and global confinement. To resolve the differences in the measured beta scalings, the ITPA topical group on Transport and Confinement has conducted coordinated experimental and modeling activities.

# 1. INTRODUCTION

If the relative gyroradius ($\rho^*$) is chosen as the size scaling parameter (as opposed to the collisionless skin depth), then determining the scaling of transport with beta ($\beta$) helps to differentiate between various proposed theories of turbulent transport that are primarily electrostatic or primarily electromagnetic. Most models of drift wave turbulence in which $E\times B$ transport is the dominant mechanism show little enhancement or even a reduction in transport with increasing $\beta$ up to some fraction (typically 50%) of the ideal ballooning stability limit [1]. On the other hand, transport from magnetic flutter, such as from micro-tearing modes or kinetic ballooning modes, increases rapidly with higher $\beta$ [2]. This is important for ITER because the fusion gain will actually start to decrease at high density and temperature if transport has a strong unfavorable $\beta$ scaling [3].

The beta scaling of energy confinement has been measured by a number of toroidal confinement devices in various regimes (*i.e.*, L-mode, H-mode) with discrepant results. Additionally, the unfavorable $\beta$ scalings derived from multi-machine confinement databases are surprisingly strong. The ITPA topical group on Transport and Confinement has coordinated experimental and modeling activity to better understand the origin of these different $\beta$ scalings. The results and conclusions from this activity are reported here.

## 2. BETA DEPENDENCE OF L-MODE TRANSPORT

In the low beta limit, turbulence should be primarily electrostatic and transport should have little dependence on beta. Several different tokamak experiments measured the β scaling of heat transport in L-mode plasmas and found a weak overall dependence [4]. An example is seen in Fig. 1 for limiter plasmas on Tore Supra where β was varied by a factor of 2 while keeping the other dimensionless parameters (*i.e.*, ρ*, ν*, q) fixed [5]. A weak increase in the effective thermal diffusivity with β is measured, $\chi_{eff} \propto \chi_B \beta^{0.31\pm0.36}$, which is in good agreement with the scaling of the energy confinement time, $B_t\tau \propto \beta^{-0.2\pm0.2}$. In addition, density fluctuations measured outside the q=1 surface did not changed visibly with β. Including results from TFTR [6] and DIII-D [7], the beta scaling of L-mode energy confinement is bounded between $B_t\tau \propto \beta^{-0.3}$ and $B_t\tau \propto \beta^{0.3}$, suggesting that electromagnetic effects are not essential to the turbulent transport process in this low β regime.

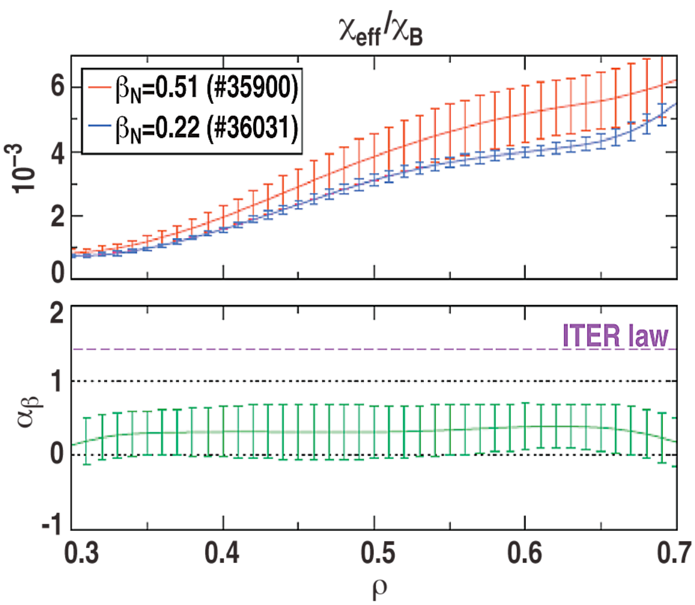


*FIG. 1. Radial profiles of (a) effective thermal diffusivity normalized to Bohm, and (b) the β scaling exponent of heat transport for L-mode plasmas on Tore Supra [5]. The dashed line marked "ITER law" shows the strong, unfavorable β dependence contained in the ITER L-mode confinement scaling relation.*

## 3. H-MODE CONFINEMENT SCALING RELATIONS

Standard regression analysis of multi-machine confinement databases consistently show a strong unfavorable scaling with beta (*e.g.*, see "ITER law" beta scaling for L-mode in Fig. 1). A particularly important example is the thermal energy confinement time from the IPB98(y,2) scaling relation for ELMy H-mode plasmas developed for the ITER project [8],

$$\tau_{\mathrm{th}}^{98\mathrm{y}2} = 0.056 I_{\mathrm{p}}^{0.93} B_{\mathrm{t}}^{0.15} n_{19}^{0.41} P^{-0.69} R^{1.97} \kappa^{0.78} \varepsilon^{0.58} A^{0.19} . \qquad (1)$$

Since this relation is close to being dimensionally homogeneous, the IPB98(y,2) scaling relation can be translated into dimensionless variables, yielding

$$B_{\mathrm{t}} \tau_{\mathrm{th}}^{98\mathrm{y}2} \propto \beta^{-0.90} \rho_*^{-2.70} \nu_*^{-0.01} q^{-3.0} \kappa^{3.3} \varepsilon^{0.73} A^{0.96} . \qquad (2)$$

This strong β degradation of confinement would favor electromagnetic models of turbulent transport, in apparent conflict with the standard picture of turbulent transport being dominated by (mainly electrostatic) ion temperature gradient modes in the core (discussed in Sec. 4), although it could also reflect an unfavorable β scaling of edge transport that degrades the H-mode pedestal height. Besides being an indication of the physical mechanism that governs transport, the β dependence of the energy confinement time strongly affects the achievable fusion gain within the operational space of ITER [3]. Resolving the apparent disparity between the β dependence of multi-machine confinement databases and individual machine parameter scans has long been a topic of interest within the ITPA Transport and Confinement group. Database analysis has shown that the poor condition of the standardized extended dataset with respect to the eight variable regression gives rise to significant uncertainty in the beta and collisionality (ν*) dependences [9]. Furthermore, the error in variables method can yield a weakened power degradation if the ratio of the error in the loss power to the error in the thermal stored energy is large enough, which would give a weaker β scaling of confinement [9]. It should be noted that the multi-machine confinement database can be fitted to an electrostatic, gyroBohm-like confinement scaling with only a small increase in the RMS error [10].

# 4. BETA DEPENDENCE OF H-MODE TRANSPORT

## 4.1. EXPERIMENT

Probing for electromagnetic effects near the ideal ballooning stability limit generally requires H-mode plasmas. Several devices around the world have measured the β scaling of global confinement and local transport in H-mode plasmas with disparate results. Figure 2 shows a summary from a review article [4] for the beta scaling exponents of thermal energy confinement, i.e., $B_t\tau_{th} \propto \beta^{-\alpha}$, determined on different tokamaks while keeping the other important dimensionless parameters fixed. These experiments on JET [11] and DIII-D [3] found that the (normalized) global confinement times and local thermal diffusivities have a weak, possibly non-existent, dependence on β, regardless of the kind of ELMs (Type I or Type III). On NSTX, a very weak dependence of confinement on β was measured even for toroidal beta values as high as 15% in plasmas with small, Type V ELMs [12].

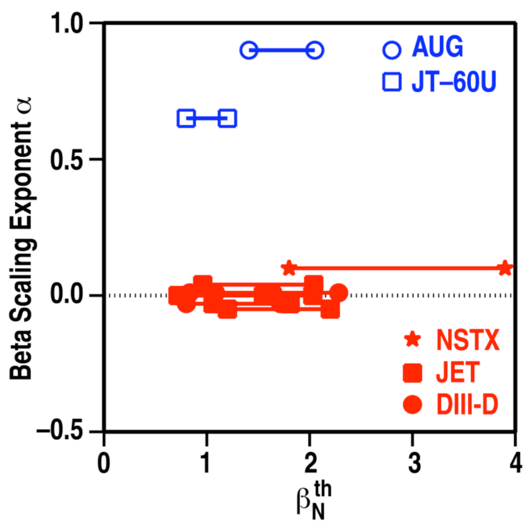


*FIG. 2. Beta scaling exponents ($B_t\tau_{th}\propto\beta^{-\alpha}$) of thermal energy confinement for H-mode plasmas on various tokamaks [4].*

However, this picture of primarily electrostatic turbulent transport was brought into question by experiments on JT-60U and ASDEX Upgrade that observed a strong unfavorable beta scaling of confinement (see Fig. 2). Experiments on JT-60U measured a square-root β degradation of energy confinement in H-mode plasmas that is intermediate between the JET/DIII-D result and the prediction of the IPB98(y,2) relation [13]. On ASDEX Upgrade, both global and local analyses yield a degradation of confinement that is almost linear in β [14]. A subsequent DIII-D experiment with joint participation by the ASDEX Upgrade team attempted to connect the disparate results by studying H-mode β scaling in both a high triangularity 'DIII-D' plasma shape and a low triangularity 'ASDEX Upgrade' plasma shape. Both high and low values of toroidal rotation are studied for the ‘DIII-D’ shape, whereas only high rotation values are studied in the ‘ASDEX Upgrade’ shape. While this experiment found a stronger β degradation of the thermal energy confinement time ($0.1 \leq \alpha \leq 0.4$) than for the previous DIII-D experiments in Fig. 2, there was no β dependence in the local thermal diffusivities outside of the ≈15% error bars, as seen in Fig. 3. The systematic difference between the local and global confinement results indicates that the profiles (including the power deposition profiles) were not exactly matched.

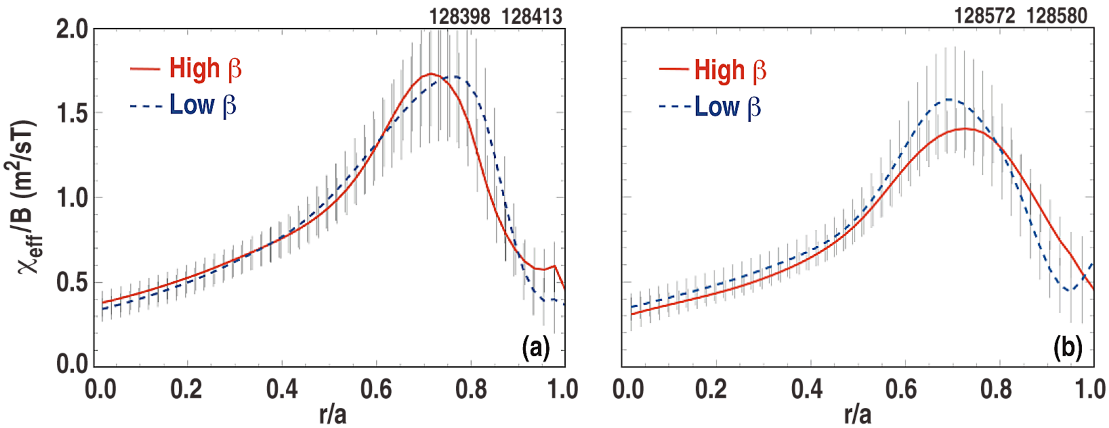


*FIG. 3. Radial profiles of the normalized effective thermal diffusivity for H-mode beta scans on DIII-D using (a) ‘DIII-D’ plasma shape with low toroidal rotation, and (b) ‘ASDEX Upgrade’ plasma shape with high toroidal rotation.*

To help identify a possible origin for the various H-mode beta dependences, a comparison was made between the device parameters and the strength of the measured beta scaling. However, as shown in Fig. 4, no single parameter clearly explains the variation in the reported β scalings. It had been suggested that different values of the upper triangularity (δ), along with the fueling condition, are possible origins of the various beta dependences [15]. A comparison of the plasma shapes on different devices is given in Fig. 4(a) but does not show any connection between the upper triangularity and the β scaling. This does not mean that a systematic shape dependence cannot be found on individual machines, *e.g.*, experiments on JET with low shape (δ=0.2) always show weak β scaling while experiments with high shape (δ=0.4) always show strong β degradation (this is in the opposite direction as suggested in [15]). Another important factor that can impact the β scaling result is experimental imperfections in profile matching. Figure 4(b) plots the thermal stored energy at the top of the H-mode pedestal divided by the total thermal stored energy. In some cases the normalized H-mode pedestal height decreases with higher β, which can result in an unfavorable β scaling even if core transport is primarily electrostatic. This situation has been seen on JET, where, despite core transport consistent with weakly β-dependent electrostatic transport, the energy confinement time exhibited strong β degradation when the edge transport increased strongly with increasing β [16]. On ASDEX Upgrade, a degradation of the pedestal by the strong gas puffing necessary in the high β cases to reach the required density cannot be excluded [14]. Given our present understanding, the effect of experimental imperfections on β scaling studies cannot be ruled out.

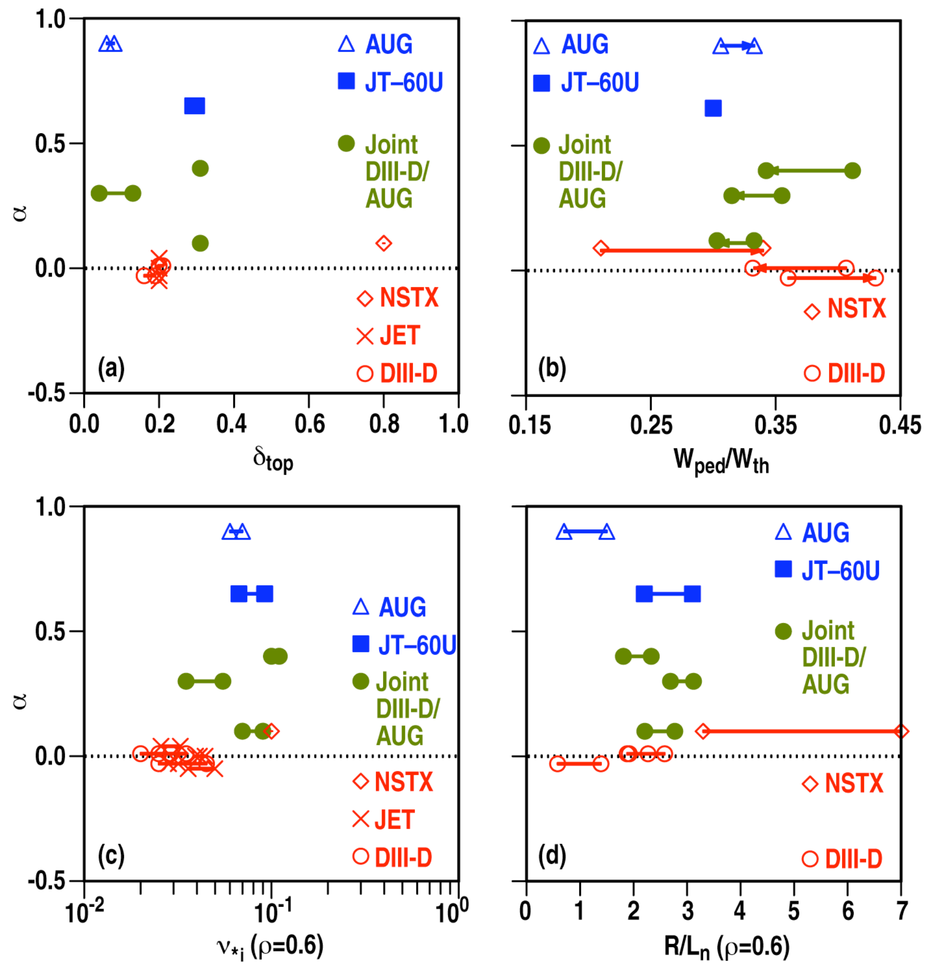


*FIG. 4. Comparison of H-mode beta scaling exponents ($B_t\tau_{th}\propto\beta^{-\alpha}$) with (a) upper triangularity, (b) normalized pedestal height, (c) ion collisionality and (d) normalized density scale length. In (b) the arrows indicate the change in the normalized pedestal height from low to high β.*

Turning to local plasma parameters, it has been suggested that micro-tearing modes, which have an unfavorable beta dependence, are a candidate to explain turbulent transport in tokamaks with both high and low aspect ratios [17,18]. Micro-tearing modes can be destabilized with sufficient beta, collisionality, and electron temperature gradient, while the growth rate peaks for flat density profiles [19]. While Fig. 4(c) shows that the strongest β scaling cases are among the most collisional, there is still a lot of variation in the β dependence between high ν* plasmas. The proximity to the Greenwald density limit ($n_{GW}$) was also examined; the experiments were noted to cover a similar range of the operational density limit and no correlation between the β scaling and $n/n_{GW}$ was found. Finally, Fig. 4(d) plots the ratio of the plasma major radius (R) to the density scale length ($L_n$). Most experiments have similar values of $R/L_n$, and while ASDEX

Upgrade with strong β degradation has a flat density profile so does a DIII-D case with no β degradation. Therefore, the role of $\nu^*$ and $R/L_n$ in affecting the β scaling is not clear from experiments alone and detailed modeling is needed.

### 4.2. MODELING

The beta scaling experiments on several machines have been simulated with a combination of gyrofluid and gyrokinetic transport models. For JET, both the Weiland and GLF23 theory-based transport models predict a stabilization of the dominant ion temperature gradient (ITG) mode with increasing β [16,20]. Reasonable agreement between the Weiland model and the core experimental results is found, including the weak β dependence, and when the model is run with the same boundary conditions and small differences in parameters as in the experiment, the agreement with experiment is improved. Linear and non-linear gyrokinetic simulations using the GENE and GS2 codes show that β degradation of confinement from the kinetic ballooning mode (KBM) is not expected for these JET plasmas since the critical β value for the onset of the KBM is higher than the values achieved in the experiment [21]. In agreement with the Weiland and GLF23 modeling for JET, the GENE code confirms that the resulting ITG mode turbulence is expected to be only weakly dependent on β (assuming the other dimensionless parameters are kept fixed).

In contrast to the above results, turbulence modeling of ASDEX Upgrade experiments using the GS2 gyrokinetic code found that micro-tearing modes are unstable in the high beta cases. As shown in Fig. 5, for plasma parameter ranges close to the conditions on ASDEX Upgrade, micro-tearing modes are the dominant instability and coexist in the spectrum with ITG modes with a comparable growth rate [22]. The linear gyrokinetic simulations find that in these high density plasmas, the β scaling of micro-instabilities is very sensitive to the density scale length when the ion temperature gradient length is close to the linear ITG threshold. While the magnetic field fluctuation amplitude for micro-tearing modes is predicted to increase with β [17,18], the contribution of micro-tearing modes to β degradation remains to be assessed quantitatively [22]. Regarding other possible turbulent modes, GS2 calculations show that, like JET, the KBM does not play a role in the β degradation observed on ASDEX Upgrade as the KBMs are destabilized at β values above the experimental range. Finally, near the plasma edge ($\rho$=0.7) where the density and $L_n$ are smaller, GS2 studies find that trapped electron modes (TEMs) are the dominant mode and that β has a destabilizing effect on the TEM.

Modeling of the DIII-D beta scaling experiment with joint participation by the ASDEX Upgrade team finds that (mainly electrostatic) ITG-mode turbulence reasonably explains the measured plasma profiles and turbulence. Simulations by the TGLF model with dominant ITG-mode transport reproduce the measured changes in the density and temperature profiles during the β scan. TGLF predicts that the thermal diffusion coefficients should have a small β dependence in the region $0.3 \leq \rho \leq 0.8$, in agreement with Fig. 3. Furthermore, the magnitude and trend with β of density fluctuations measured by beam emission spectroscopy (BES) were found to be in reasonable agreement with "flux matching" GYRO simulations for electrostatic ITG-mode turbulence [23], as seen in Fig. 6. While the β scaling for these DIII-D experiments was weaker than reported on ASDEX Upgrade, the regimes were perhaps not far from connecting. Linear calculations for DIII-D that artificially scale ν* and $R/L_n$ to better mimic ASDEX Upgrade find micro-tearing modes to become more important.

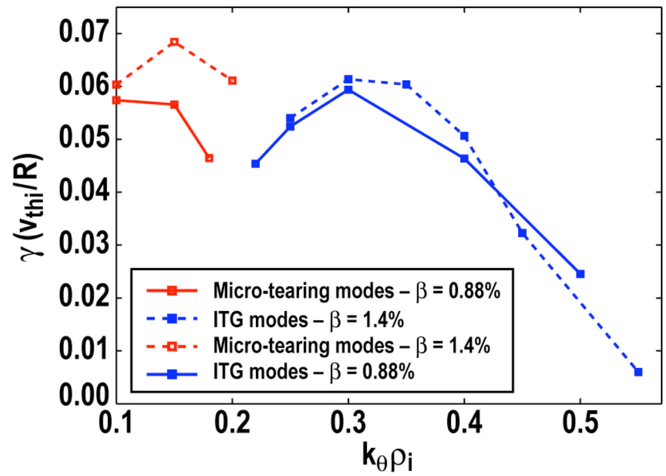


*FIG. 5. Growth rate spectra from GS2 for $R/L_n$=1.5 for an H-mode beta scan on ASDEX Upgrade [22].*

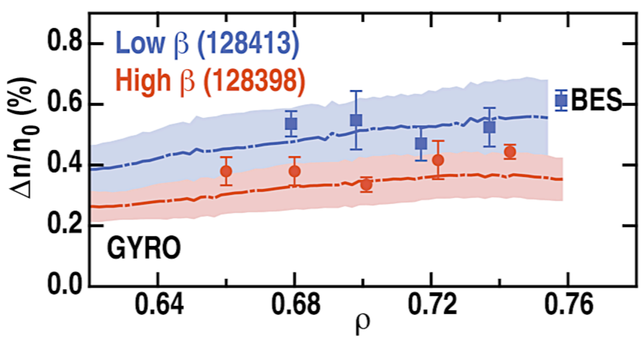


*FIG. 6. Comparison of BES density fluctuations and "flux matching" GYRO simulations with electrostatic ITG-mode turbulence for a H-mode beta scan on DIII-D.*

## 5. CONCLUSIONS

While the β scaling of energy transport is observed to be weak in L-mode plasmas, both strong and weak β degradation of energy confinement has been reported in H-mode plasmas. No single experimental parameter (*e.g.*, δ, $W_{ped}/W_{th}$, ν*, $R/L_n$) is able to explain the variation in the reported β scalings on the different tokamaks. However, theory-based transport modeling gives insight into the β dependence on individual devices. For JET and DIII-D, the dominant ITG mode is predicted to give rise to a weak β dependence in the core, in agreement with experiments. Modeling of the JET experiments also clearly demonstrates the importance of mismatches in the plasma profiles and the important role edge/boundary transport. For plasma parameter ranges close to the conditions on ASDEX Upgrade, micro-tearing modes are predicted to be the dominant instability, although the contribution of micro-tearing modes to β degradation remains to be assessed quantitatively. An interesting question is why a strong β degradation of confinement is not observed on NSTX, where micro-tearing modes are also calculated to be significant [19,24]. Perhaps E×B shear, the peaked density profile or global effects limit the micro-tearing transport for the high β plasmas on NSTX, or perhaps a favorable pedestal scaling with β may have an offsetting effect. This open issue needs more study, and the implications for confinement scaling relations in low aspect ratio tokamaks should be addressed. In summary, the disparate beta scalings may be explained by either different dominant turbulence modes, or experimental imperfections such as changes in the H-mode pedestal height during the β scan. The former points out the need to determine whether micro-tearing modes are expected to appear in ITER.

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