Sensitivity Study of Predictions of an ITG-based Transport Model

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This is a status report of work in progress. Enclosed is the contents of poster Q7S37, as presented at the Fortieth Annual Meeting of the American Physical Society Division of Plasma Physics, New Orleans, November 16-20, 1998 (poster Q7S37, abstract in Bull. American Phys. Soc. **43**, 1877 (1998). A more extensive study, with more parameter variations, is in preparation. Among other things, the final report will include modifications to the figures on p. 5 to reflect a further 20% increase in the nonlinear threshold in R/L_{Ti} found in recent gyrokinetic simulations (though the addition of collisions and non-adiabatic electrons may offset this).

Available online at http://w3.pppl.gov/~hammett/work/1998/aps98.pdf.

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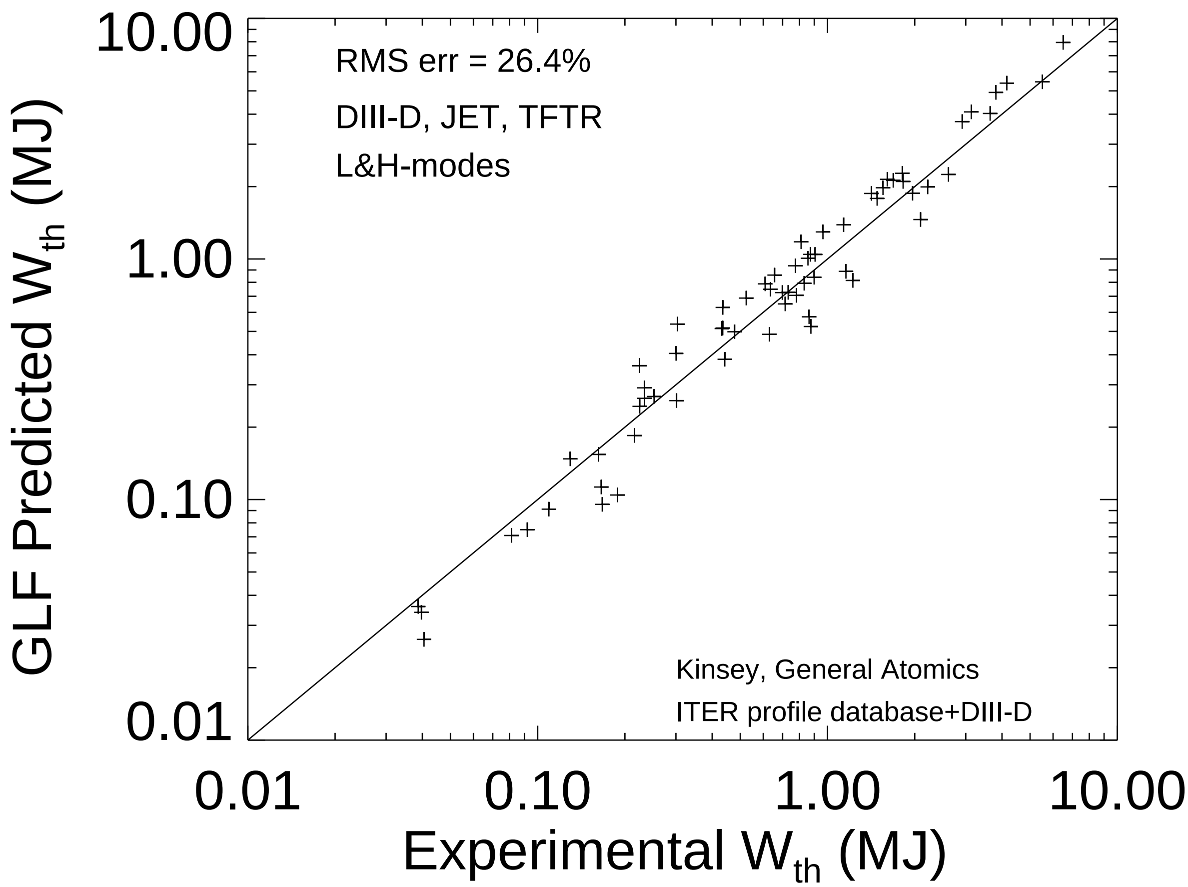
We investigate the effects of various assumptions in an ITG-based transport model on the predicted fusion power performance of various tokamak reactor designs. Among other sources of variability, the effect of modifying the IFS-PPPL model (originally based on gyrofluid simulations) to roughly fit the lower turbulence levels of gyrokinetic simulations is shown. There is a strong dependence on the assumed H-mode pedestal temperature. Various models for the scaling of the pedestal temperature are considered[1], but they all share some common features that suggest that performance might be improved significantly for compact, higher field tokamak designs with stronger plasma shaping[2] and density peaking, such as in ARIES-RS or similar designs. However, more work is needed to be confident of these scalings.

This work supported by DoE Contract DE-AC02-76CH03073, the Numerical Tokamak Turbulence Project, and NERSC computing resources.

[1] M. Kotschenreuther, W. Dorland, et.al., Proc. 16th Int. Conf. Plasma Physics and Control. Nucl. Fusion Res. (IAEA 1996); F.W. Perkins et.al. ibid; T. Hatae et.al., Plasma Phys. Control. Fusion **40** 1073 (1998).

[2] Y. Kamada et.al. Plasma Phys. Control. Fusion **38**, 1387 (1996).

Transport Model Based on Turbulence Simulations Follows Many Experimental Trends



• GLF23 transport model by Waltz et.al fitted to Beer et.al. nonlinear 3-D gyrofluid simulations of ITG/trapped-electron turbulence.

• Encouraging results so far, but many caveats: uses measured density and rotation profiles, uses measured temperatures at $r/a = 0.9$, electrostatic turbulence simulations need extension to magnetic fluctuations ($\sim$10$\times$CPU time), gyrofluid/gyrokinetic discrepancy, etc... Much future work needed to be more accurate over a wider range of plasma parameters.

• Rescaled GLF23, $\downarrow \chi$ and $E\times B$ shear, improves to RMS error $\approx 19\%$.

II. SIMULATION RESULTS AND RANKING OF MODELS

To assess the performance of each transport model, quantitative comparisons are made between the model predictions and the experimental data for both global and local quantities. Figure 1 shows that the Multimode model yields the best overall agreement with the database followed by the IFS/PPPL model (without E×B shear), IIF, and GLF23 (with E×B shear) models, respectively.

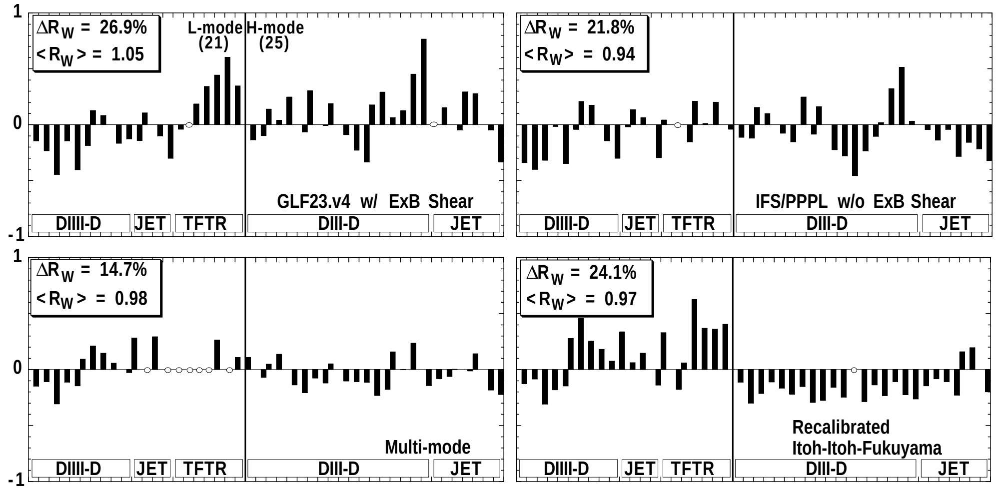


Fig. 1. Stored energy offset for the GLF23, IFS/PPPL, Multimode, and IIF models.

Here, the stored energy offset f_W, defined as W_S/W_X–1, is plotted versus discharge for each of the four transport models. The L– and H–mode results are divided left and right by a thick black line with the discharges also being conveniently grouped according to machine. Here, a positive (negative) offset indicates the model overpredicts (underpredicts) the stored energy. A hollow circleis shown when no numerical result was found for a particular discharge. In the upper left corner of each panel is the average and the root-mean-square error (rms) for the total stored energy.

Furthermore, we find that the ranking of the models is independent of the figure of merit chosen. Here, the global figures of merit include the average $\left\langle R_W \right\rangle$ and rms error ΔR_W for the total stored energy

$$\left\langle R_W \right\rangle = \sum_i \left(W_{si} / W_{xi} \right) \Big/ N \qquad \Delta R_W = \sqrt{ \sum_i \left(W_{si} / W_{xi} - 1 \right)^2 \Big/ N } \tag{1}$$

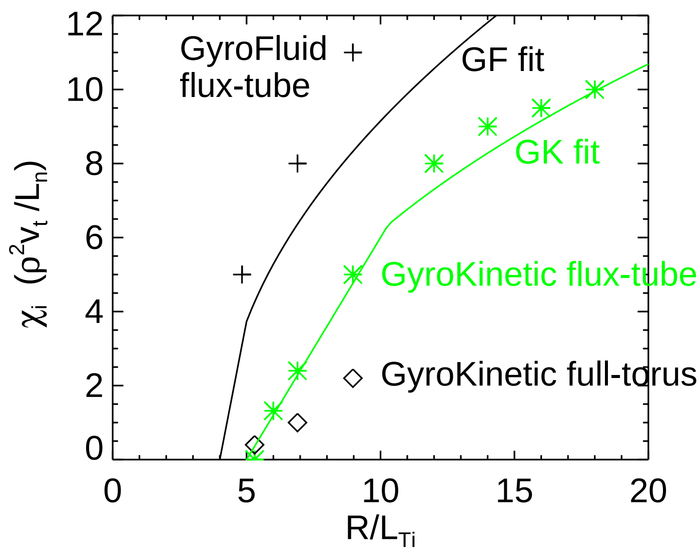
where N is the total number of discharges and $W_{s,x}$ refer to the simulation and experimental stored energies, respectively. The local figures of merit include the offset f_T and rms error σ_T between the predicted and experimental temperature profiles where

$$f_T = \sum_i \left(T_s - T_x \right) \Big/ \sqrt{ \sum_i T_x^2 } \qquad \sigma_T = \sqrt{ \sum_i \left(T_s - T_x \right)^2 } \Big/ \sqrt{ \sum_i T_x^2 } \tag{2}$$

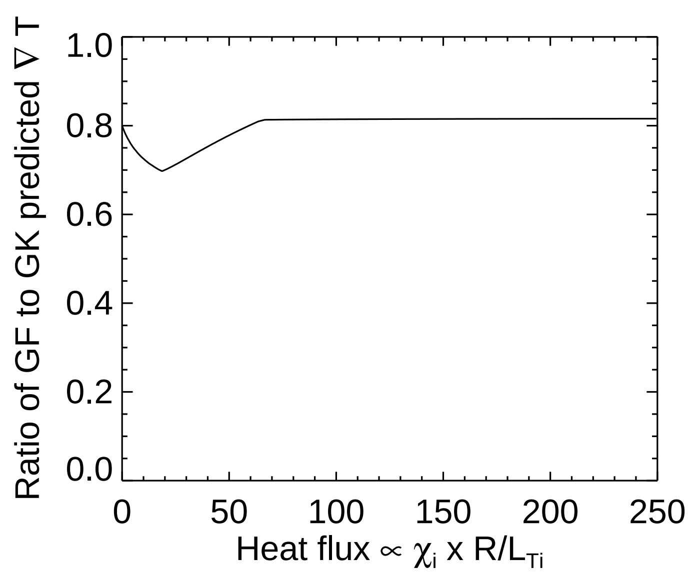
Table 1 shows the average and rms error for the total stored energy along with the rms error and average offset for the temperature profiles. Notice that agreement with the database gets worse when E×B shear is included in the IFS/PPPL model, but agreement improves when

Gyrofluid/gyrokinetic simulation differences correspond to 20-30% differences in the predicted temperature gradient.

• Dimits (LLNL) has done a nice job demonstrating that particle noise is not a problem in his gyrokinetic particle simulations.



• Turning this plot around, for a fixed amount of heat flux, $\propto \chi\nabla T$, the temperature gradient predicted by the gyrofluid-based IFS-PPPL model is 20-30% low compared to the gyrokinetic fit.



- These differences might be reduced by a weak amount of collisions (which may be particularly important near marginal stability by affecting narrow resonances, or by damping zonal flows) and by other drives such as non-adiabatic electrons which will push into a stronger turbulence regime and alter marginal stability.

- In some sense the present differences are not huge.

  - The differences in the predicted ∇T are only 20-30%
  - Even after modifying the IFS-PPPL model to fit these gyrokinetic results, the resulting ITER predictions are still very sensitive to the uncertain edge pedestal temperature, and give low Q at low pedestal temperatures or reduced density.

- Nevertheless, fusion power is proportional to T^2 and one would like more accurate simulations. Modifications of gyrofluid closures are being investigated to improve the comparisons.

our model with finite-size particles but the number of particles per shortest wavelength and this can be orders of magnitude larger than the particle number per cell. This empirical method of finding the number of particles for convergence of results, using a given particle to grid interpolation method, is currently the best method for testing the reliability of the simulations.

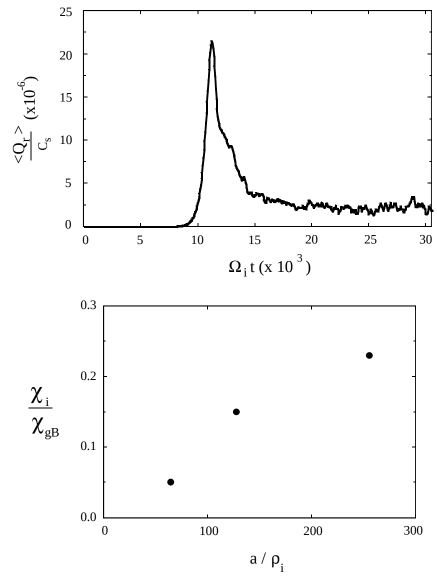


Figure 6. Time evolution of the global radial ion thermal flux (for the smallest system size $a = 64\rho_i$) and the time interval corresponds to $\tilde{t} = tL_T/c_s$ = 0–635. The ion thermal diffusivity against system size is shown in the lower part the figure.

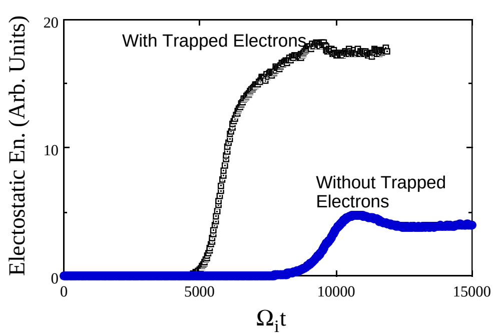


Figure 7. Time evolution of the total electrostatic energy for the case with adiabatic electrons only and with the inclusion of non-adiabatic electron density response from trapped electrons.

Modified version of IFS-PPPL transport model to better fit gyrokinetic simulations

The original IFS-PPPL transport model was based on nonlinear gyrofluid simulations of ITG turbulence, with adjustments to give more accurate gyrokinetic linear critical gradients. The final result is of the form:

$$\chi_{GF} = \frac{cT}{eB}\frac{\rho}{R}\min\left[\left(\frac{R}{L_{Ti}} - \frac{R}{L_{Ti,crit}}\right), \left(\frac{R}{L_{Ti}} - \frac{R}{L_{Ti,crit}}\right)^{0.5}\right] g(\frac{T_i}{T_e}, q, \hat{s}, ...)$$

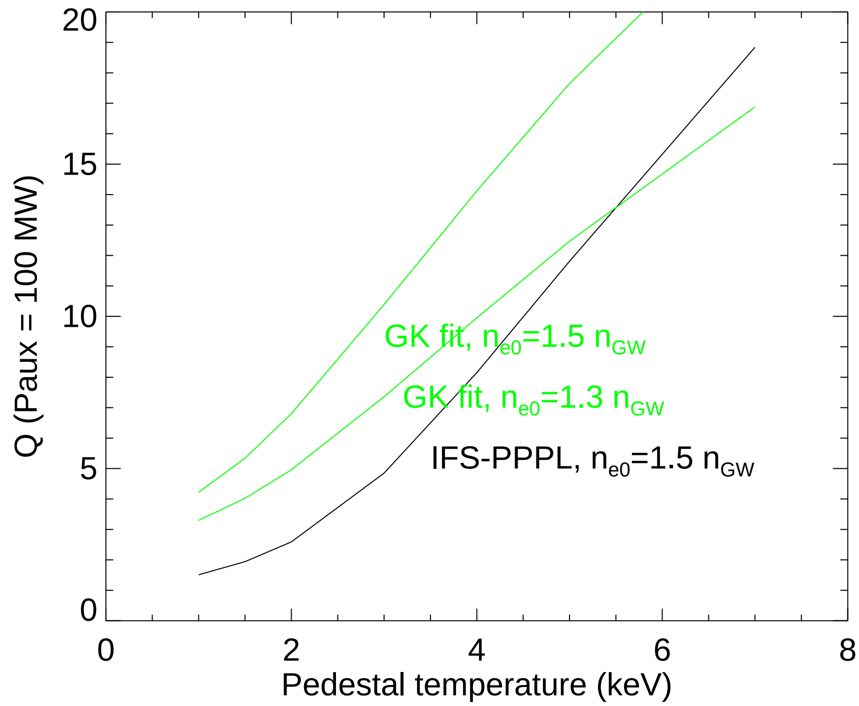
To investigate the sensitivity of predictions of Q to assumptions about χ, we modify this to better fit the gyrokinetic simulations by Dimits et.al. (LLNL) for the DIII-D test case temperature gradient scan:

$$\chi_{GK} = \frac{cT}{eB}\frac{\rho}{R}\min\left[0.32\left(\frac{R}{L_{Ti}} - \frac{1.25R}{L_{Ti,crit}}\right), 0.736\left(\frac{R}{L_{Ti}} - \frac{1.25R}{L_{Ti,crit}}\right)^{0.5}\right] g(\frac{T_i}{T_e}, q, \hat{s}, ...)$$

This is shown on the 2cd page back, using the form for g and from Dorland et.al.'s 1994 IAEA paper, which is appropriate for comparing with simulations that assumed adiabatic electron, and using $R/L_{Ti,crit} = 4.0$, which is appropriate for this simple $s - \alpha$ circular geometry test cases (with $\alpha = 0$). In the following pages, we will use this same GK-based modification (linear slope multiplied by a factor 0.32, square-root region by a factor of 0.736, $R/L_{Ti,crit}$ multiplied by 1.25) but use the forms for g and $R/L_{Ti,crit}$ from Kotschenreuther et.al.'s 1994 APS paper, which includes futher destabilizing influences of non-adiabiatic electrons.

This is a reasonable fit for these gyrokinetic simulations, but more work needs to be done to check fits with gyrokinetics over a much wider set of parameters.

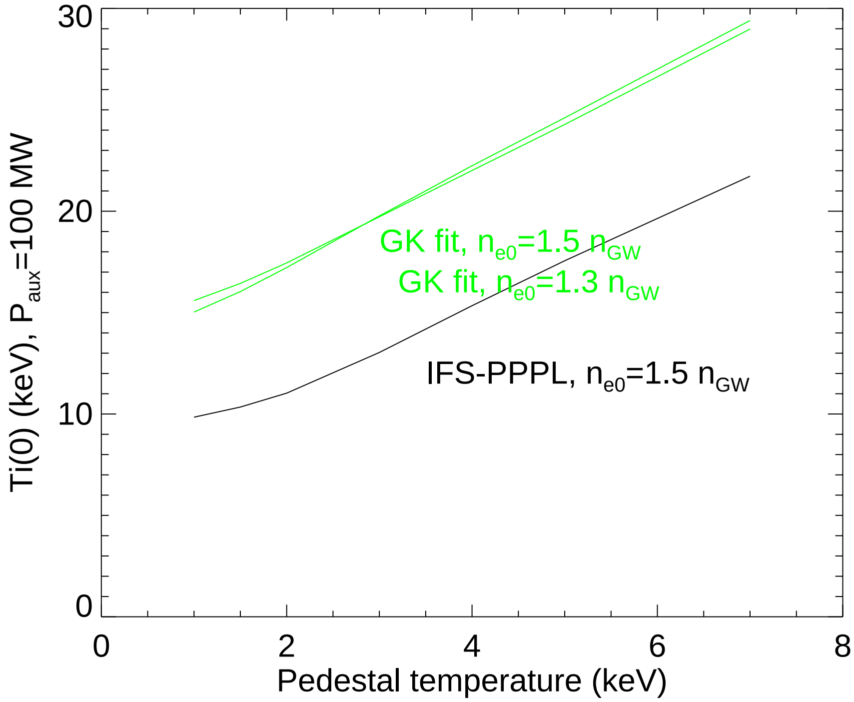
Comparison of predictions of Q in ITER from original IFS-PPPL model, and modified version to fit gyrokinetic simulations



• Gyrokinetic-fit version causes predicted Q to rise some, but the original point remains that the results are sensitive to the assumed edge pedestal temperature, which is uncertain. There is a risk of low Q, particularly at low density.

• The uncertainties are large, and it may be that ITER's pedestal temperature and confinement would be acceptable for ignition. Other sources of uncertainty which need better treatment, in addition to a better understanding of the edge transport barrier and the achievable density and density peaking, include the effects of elongation and plasma shaping, plasma rotation, and fully electromagnetic fluctuations with non-adiabatic electrons [Combining several of these effects together might give high Q or ignition in ITER in some cases. A more complete sensitivity study will be done soon.]

ITER-96 baseline scenario, $n_e = 1.3 \times 10^{20}/m^3 = 1.5\, n_{\mathrm{Greenwald}}$, $\tau_{He*}/\tau_E = 10$.



Ti(0) (keV), P_{aux}=100 MW
Pedestal temperature (keV)
GK fit, n_{e0}=1.5 n_{GW}
GK fit, n_{e0}=1.3 n_{GW}
IFS-PPPL, n_{e0}=1.5 n_{GW}
0
10
20
30
0
2
4
6
8

Modifications to gyrofluid closures being investigated to improve comparisons with gyrokinetic simulations.

• **Better treatment of Rosenbluth-Hinton undamped components of poloidal flow**. Preliminary closure modification reproduce the non-linear upshift in the critical gradient seen by Dimits, and reduces χ by ~ 35% in stronger turbulence regimes. New closure has an un-damped component of flow, but needs further improvement at very low k_r, which may further lower χ.

• **Frequency-dependent closures**: As pointed out in the gyrofluid approach of Chang and Callen, gyrofluid closures can be determined exactly linearly. In a local approximation this will involve functions of

$$Z^2\left(\sqrt{\omega/\omega_d}\right) = Z^2\left(\sqrt{\omega/(\vec{k}\cdot\vec{v}_d)}\right)$$

branch cut leads to damping only for modes which propagate in the same direction as the toroidal drifts of the particles. Our present Pade approximation gives a small residual imaginary component even for modes which propagate opposite to the particles...

Mattor suggests using an instantaneous WKB approximation for $\omega = i\partial\Phi/\partial t/\Phi$, with the rationale that

• near marginal stability, where $\gamma \ll \omega$, this is an accurate measure of ω, and thus improves the calculation of marginal stability, and

• far from marginal stability, this instaneous approximation for ω will vary in time and sample the Z function over a relevant range of ω's.

We are in the process of investigating how much χ might change in various parameter regimes with such modifications.

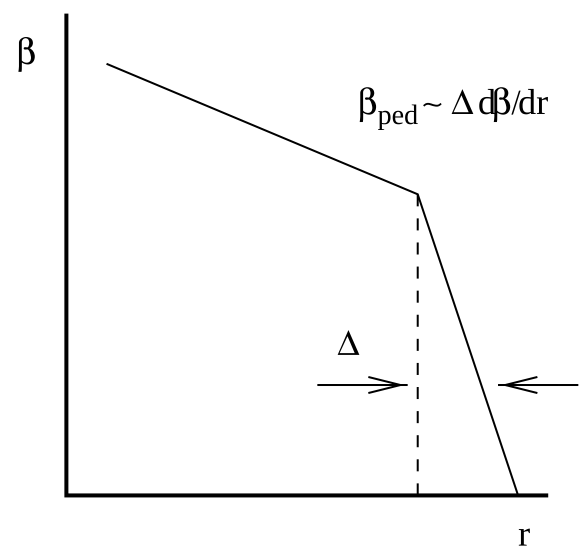
If the ITG χ drops too much, while this would give more favorable predictions for large reactors, it might have trouble explaining present experiments. If the ITG χ is no longer large enough to force the plasma profiles to be near marginal stability, it may be hard to explain certain experimental features such as the dependence of core transport on edge conditions, fast transport responses to perturbations, non-gyro-Bohm regimes, or the strength of some effects that appear to enter at present primarily through modifying $R/L_{Ti,crit}$.

On the other hand, there are less-stiff transport models like the Multi-Mode Model, which supplement a smaller ITG model with other transport mechanisms (such as resistive ballooning), and which fits many equilibrium profile measurements fairly well and predicts much better performance for ITER.

The effect of modified gyrofluid closures (to better fit gyrokinetic results) on χ is an important issue and is being actively investigated. Electromagnetic effects, weak collisions, and non-adiabiatic electrons may also introduce important modifications.

Edge pedestal scalings very uncertain, but most favor high-field, compact designs with strong shaping and density peaking

• Wide range of theory & expt. evidence: $\Delta/R \propto \rho_{*\theta}$ (JT-60U, JET), $\rho_{*\theta}^{2/3-1/2}$, $\beta_{pol}^{1/2}\rho_*^0$ (very interesting DIII-D evidence of a second stable edge, which would have a more favorable scaling to reactors)



• Making two assumptions:

1. Width $\Delta \propto \sqrt{\epsilon}\rho_\theta \propto \rho q/\kappa\sqrt{\epsilon}$
2. stability limit $\partial\beta/\partial r \propto [1+\kappa^2(1+10\delta^2)]/Rq^2$ (rough fit to JT-60U, Koide et.al., Phys. Plasmas **4**, 1623 (1997), other expts. also show improvement with shaping)

gives

$$T_{ped} \propto \left(\frac{n_{Gr}}{\langle n\rangle}\right)^2 \left(\frac{\langle n\rangle}{n_{ped}}\right)^2 \left[\frac{1+\kappa^2(1+10\delta^2)}{1+\kappa^2(1+2\delta^2-1.2\delta^3)}\right]^2 \frac{A_i R}{\kappa^2 a}$$

(Hammett, Dorland, Kotschenreuther)

Possible directions to improve pedestal temperature

Using this T_{ped} formula (with a $\Delta \propto \rho_\theta$ assumption) to scale from JET to some proposed reactor designs:

	R	a	B	I_p	n_{ped}	$\frac{n_{ped}}{n_{Gr}}$	$\frac{n_{ped}}{\langle n \rangle}$	κ_x	δ_x	T_{ped}
	m	m	T	MA	$10^{20}/m^3$					keV
JET-like	2.92	0.91	2.35	2.55	0.4	0.4	~ 1	1.76	.21	2.1
ITER-96	8.14	2.80	5.68	21.0	1.3	1.5	1	1.68	.26	0.2^*
lower n_{ped}	8.14	2.80	5.68	21.0	0.6	0.7	.70	1.68	.26	0.9^*
ITER-ham	6.30	1.81	6.58	13.0	0.86	0.68	.8	1.73	.30	1.3
ITER-lam	6.45	2.33	4.25	17.0	0.64	0.64	.8	1.86	.50	2.3
Aries-RS	5.52	1.38	7.98	11.3	1.4	0.74	.67	1.89	.50	3.0
BPX-AT	2.0	0.5	10.0	6.25	3.6	0.45	.80	2.0	.4	4.1

* should add $(nT)_{sol}/n_{ped}$ which could be as high as ~ 0.5 keV.

Other pedestal scalings (such as assuming $\Delta \propto \rho_\theta^{1/2}$, etc.) predict even higher pedestal temperatures for all of these proposed devices. But it is encouraging that even with this most pessimistic scaling, it may be possible to achieve relatively high pedestal temperatures by going to high field, smaller size, stronger plasma shaping, and density peaking.

(Hammett, Dorland, Kotschenreuther)

Pedestal width $\Delta \propto \sqrt{Rq\rho}$ predicts higher edge pedestal temperatures

Scaling from JET to some proposed reactor designs:

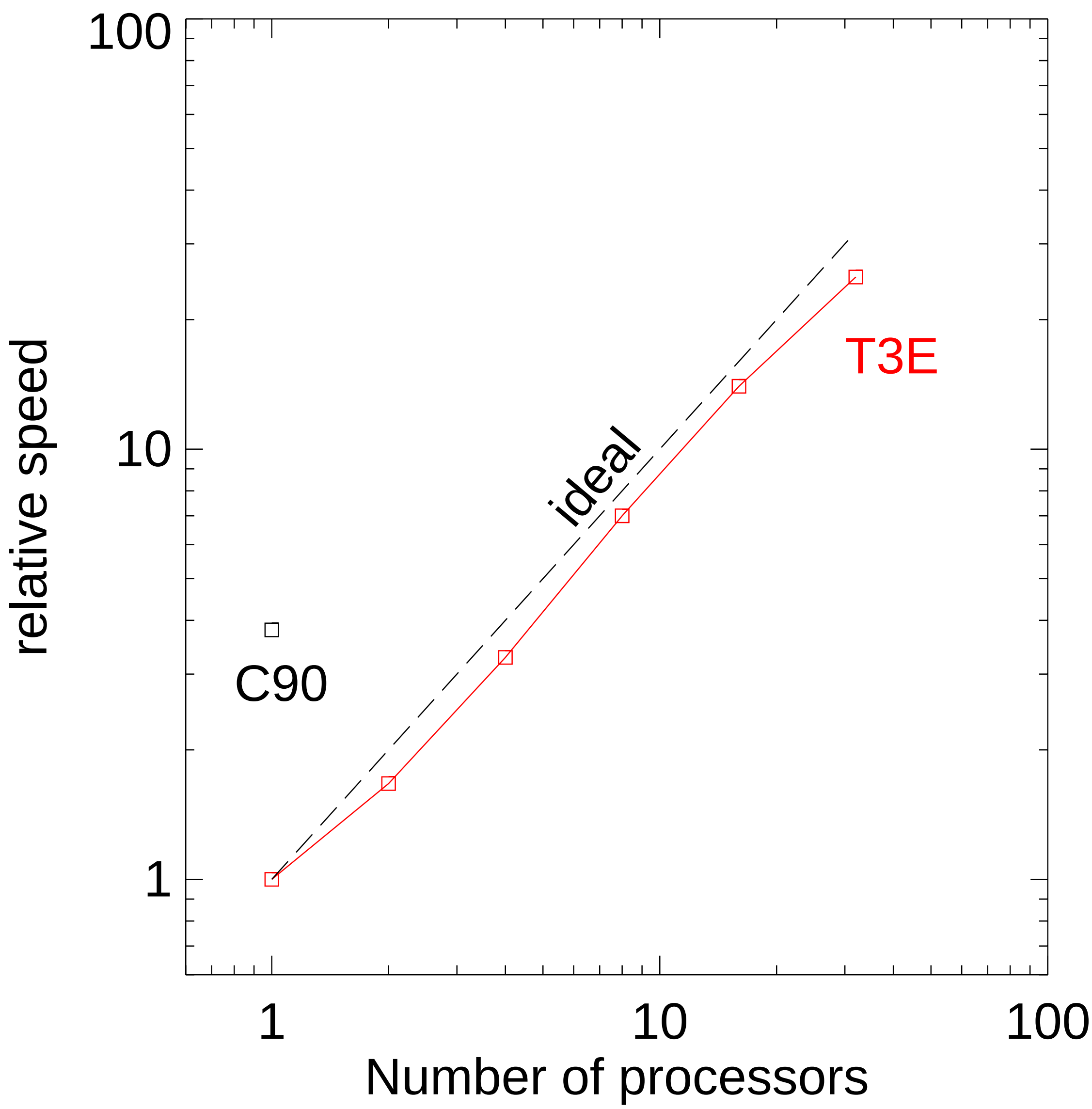
	R m	a m	B T	I_p MA	n_{ped} $10^{20}/m^3$	$\frac{n_{ped}}{n_{Gr}}$	$\frac{n_{ped}}{\langle n \rangle}$	κ_x	δ_x	T_{ped} keV
JET-like	2.92	0.91	2.35	2.55	0.4	0.4	~ 1	1.76	.21	2.1
ITER-96	8.14	2.80	5.68	21.0	1.3	1.5	1	1.68	.26	1.3*
lower n_{ped}	8.14	2.80	5.68	21.0	0.6	0.7	.70	1.68	.26	3.7*
ITER-ham	6.30	1.81	6.58	13.0	0.86	0.68	.8	1.73	.30	4.2
ITER-lam	6.45	2.33	4.25	17.0	0.64	0.64	.8	1.86	.50	5.6
Aries-RS	5.52	1.38	7.98	11.3	1.4	0.74	.67	1.89	.50	7.0
BPX-AT	2.0	0.5	10.0	6.25	3.6	0.45	.80	2.0	.4	5.9

* should add $(nT)_{sol}/n_{ped}$ which could be as high as ~ 0.5 keV.

If the DIII-D scaling of $\Delta/R \propto \rho_*^0 \sqrt{\beta_{pol}}$ is used (which might be indicative of a second-stability edge?), even higher pedestal temperatures would be predicted.

(Hammett, Dorland, Kotschenreuther)

Gyrofluid code scales well on T3E*



*Thanks to recent port to the T3E using MPI (and optionally shmem) by Peter Liu (IFS) and BIll Dorland (U. Maryland).