Tests of the IFS-PPPL Transport Model with Sheared Flow Stabilization

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Abstract

We test the IFS-PPPL transport model by comparing predicted temperatures to measurements in DIII-D, JET, and TFTR (obtained from the TFTR and ITER profile databases). We examine the evidence for sheared flow stabilization in a variety of rotation scans in TFTR, and discuss its possible importance in uni-directional injection experiments in DIII-D and JET. The TFTR rotation scans include D and DT discharges in the L-mode and supershot regimes; the DIII-D and JET discharges are in the L- and H-modes. Neoclassical 'corrections' to the measured impurity flow speeds are included in the analysis. Nonlinear gyrofluid simulations of sheared flow effects provide a parametric form for the stabilization term. A hybrid of predictive and analysis methodologies is used in solving the power balance equations. The predicted $T_{\rm e}$ and $T_{\rm i}$ are used in calculating the theoretical diffusivities, the ion-electron temperature equilibration power, and the convected power. The measured temperatures, density and $Z_{\rm eff}$ are used in other calculations, e.g., for auxiliary heating rates.

Overview

- $E \times B$ flow shear is associated with the formation of transport barriers in H- VH-, and ERS-modes.
- We examine the effect of sheared flows on the reduction of core transport.
- Temperatures are predicted using the IFS-PPPL transport model.
- Including sheared flow stabilization improves the predictions of DIII-D and JET H-mode ρ_* experiments, and of TFTR experiments on ρ_* scaling, isotope scaling, and a rotation scan.
- We find that sheared flows are more important at one end of the ρ_* range in the DIII-D and TFTR ρ_* experiments, thereby masking the underlying ρ_* dependence of plasma transport.
- However, further work is needed to fully develop the theoretical model for the effects of sheared flows on transport.

Sheared Flow Stabilization

- Differential rotation limits the growth of turbulent eddies, thereby reducing transport.
- E_r shear causes the differential rotation.
- The radial electric field is estimated from the radial force balance equation and measurements of the impurity toroidal rotation speed:

$$\nabla_r p_j = n_j Z_j e(E_r + V_\phi B_\theta - V_\theta B_\phi)$$

- This estimate includes
  1. neoclassical contributions to the measured impurity flow,
  2. the classical diamagnetic flow,
  3. damped (but finite) poloidal flow.
- The $E \times B$ shearing rate, in general geometry, is

$$\gamma_{\text{shear}} = \frac{r\kappa}{q(1-\Delta')^2}\frac{\partial}{\partial r}(\frac{cE_r}{RB_\theta})$$

- The diffusivities are reduced by the factor

$$(1 - \gamma_{\text{shear}}/\gamma_{\text{linear}}),$$

  where γ_{linear} is the peak linear growth rate.
- We do not yet include the destabilizing effects of parallel shear.

Profile Modeling Database

Experimental data is assembled, edited, and processed by codes such as **ONETWO**, **SNAP**, **TOPICS**, and **TRANSP** which generate a transport analysis of the shot. Results from many tokamaks have been contributed to the profile modeling database at the ITER Joint Central Team site.

- The major elements of experimental data typically used by the analysis codes are profiles of the radiated power, electron and ion temperatures, and electron density, together with plasma size, I_{p}, B_{o}, V_{loop}, neutral beam power, beam voltage and geometry, plasma and beam species, H_α intensity, visible bremsstrahlung intensity, and $\Delta Z_{\mathrm{eff,metals}}$.

- The measured profiles are transformed from major radius to minor radius including the effects of the Shafranov shift.

- The analysis codes also calculate the neutral beam deposition, first orbit losses, fast ion charge exchange, fast ion heating of electrons and thermal ions, fast ion density and, by subtraction from n_{e}, the thermal ion density.

- The particle flux is given by the calculated ionization of neutral beams and thermal neutral gas (influx $\propto$ H_α intensity).

- The 'source and sink' terms, as well as the basic kinetic data, are placed in the database.

Testing Methodology

- Profiles of densities, heating powers, radiation and charge exchange losses, etc., are read from the profile database. These are calculated using only the measured temperatures; in contrast to a fully predictive transport code these are not influenced by errors in the temperatures predicted by transport models.

- The temperatures are predicted by solving the power balance equations using theoretical thermal diffusivities.

- The measured electron density and the database estimate of the thermal ion density are used in the temperature predictions.

- The predicted electron and ion temperatures are used to calculate the theoretical thermal diffusivities, the temperature equilibration power, and the convected power.

- Simultaneous prediction of both temperatures or prediction of the temperature of a single species is possible. If a single temperature is being predicted the other temperature is fixed at the measured value.

- The predicted temperatures are written to databases at PPPL and ITER for comparison with other predictions and for further processing to assess the goodness of fit.

Transport Equations

We solve the steady state 1-d diffusion equation which is based on energy conservation:

$$\frac{\partial(1.5nT)}{\partial t} = 0 = -\frac{1}{V'}\frac{\partial}{\partial \xi}[Sq] + Q,$$

where the net heating power densities are

$$Q_e = Q_{\mathrm{b,e}} + Q_{\mathrm{ICRH,e}} + Q_{\alpha,\mathrm{e}} - Q_{\mathrm{rad}} + Q_{\mathrm{ie}} + Q_{\mathrm{OH}},$$

$$Q_i = Q_{\mathrm{b,i}} + Q_{\mathrm{ICRH,i}} + Q_{\alpha,\mathrm{i}} - Q_{\mathrm{cx}} - Q_{\mathrm{ie}},$$

the conducted plus convected power flows are

$$q_e = -n_{\mathrm{e}}\chi_{\mathrm{e}}\nabla\xi\frac{\partial T_{\mathrm{e}}}{\partial \xi} + \gamma_{\mathrm{conv}}T_{\mathrm{e}}\Gamma,$$

$$q_i = -n_{\mathrm{i}}\chi_{\mathrm{i}}\nabla\xi\frac{\partial T_{\mathrm{i}}}{\partial \xi} + \gamma_{\mathrm{conv}}T_{\mathrm{i}}\Gamma,$$

and the geometrical quantities $V(\xi)$, $S(\xi)$, and $\nabla\xi = \frac{\partial\xi}{\partial\rho}$ are provided by the profile database, and γ_{conv} is the theory-dependent convective multiplier (convection is included in χ in some models).

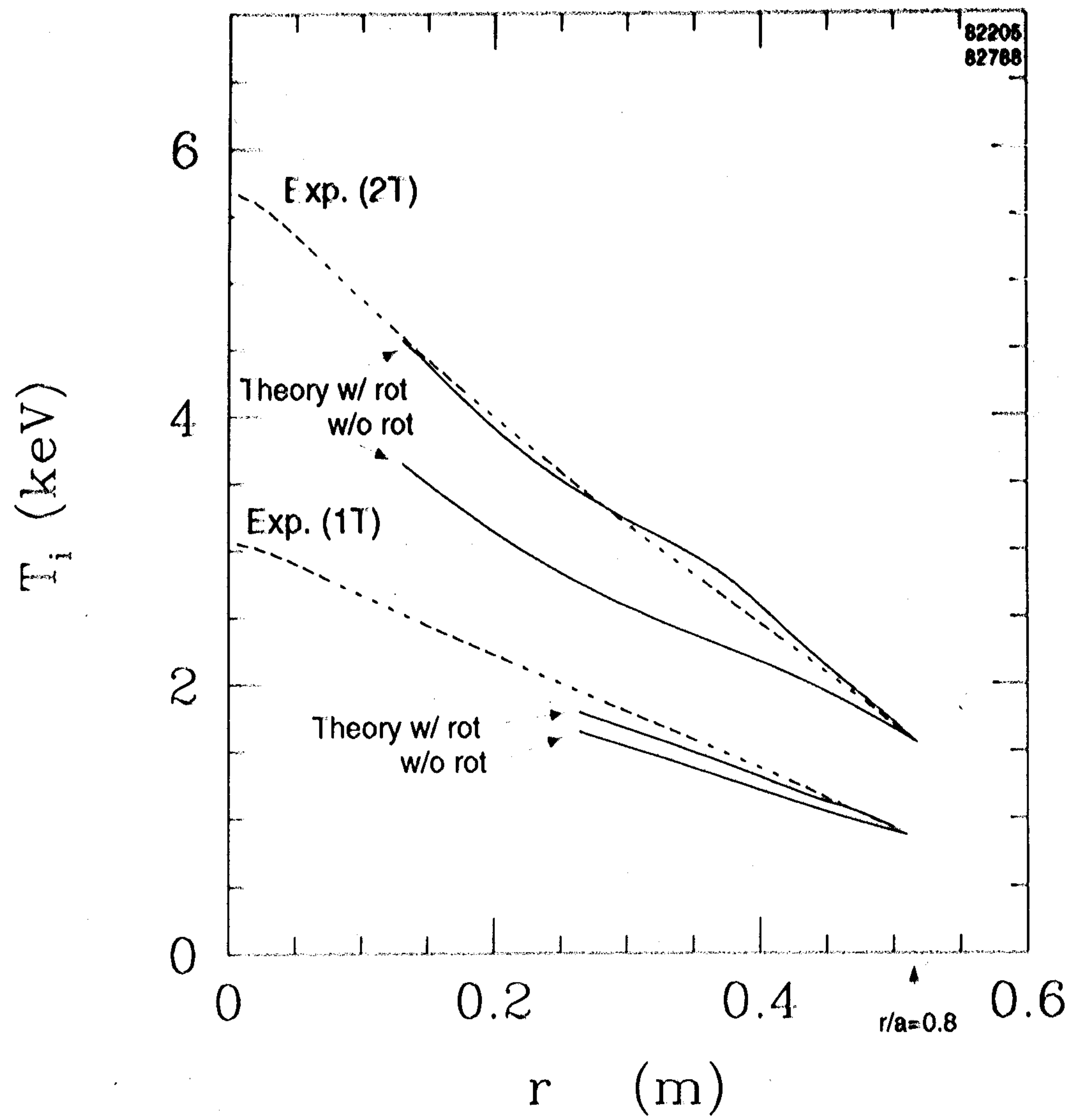
As in a fully predictive transport code the predicted temperatures are used in evaluating the thermal diffusivities, the electron-ion coupling and convected power.

The predicted temperatures are not used in the calculation of ohmic or auxiliary heating. The analysis code supplying data to the profile database calculates the heating using the measured temperatures, and the 'sources and sinks' are not recalculated in the post-processor.

Summary

- **We examine the effect of sheared flows on the reduction of core transport.**
- **Temperatures are predicted using the IFS-PPPL transport model.**
- **Including sheared flow stabilization improves the predictions of DIII-D and JET H-mode ρ_* experiments, and of TFTR experiments on ρ_* scaling, isotope scaling, and a rotation scan.**
- **We find that sheared flows are more important at one end of the ρ_* range in the DIII-D and TFTR ρ_* experiments, thereby masking the underlying ρ_* dependence of plasma transport.**
- **However, further work is needed to fully develop the theoretical model for the effects of sheared flows on transport.**

Sheared Rotation has a significant effect on D-IIID ρ_* scan (H-mode, ITER demo case)



Extension of original IFS-PPPL transport model to include an approximate treatment of sheared flows, based on Waltz's fit to sheared flow simulations:

$$\chi_i = \chi_{\text{IFS-PPPL}} \times \left(1 - \frac{\gamma_{E\times B}}{\gamma_{lin}}\right)$$

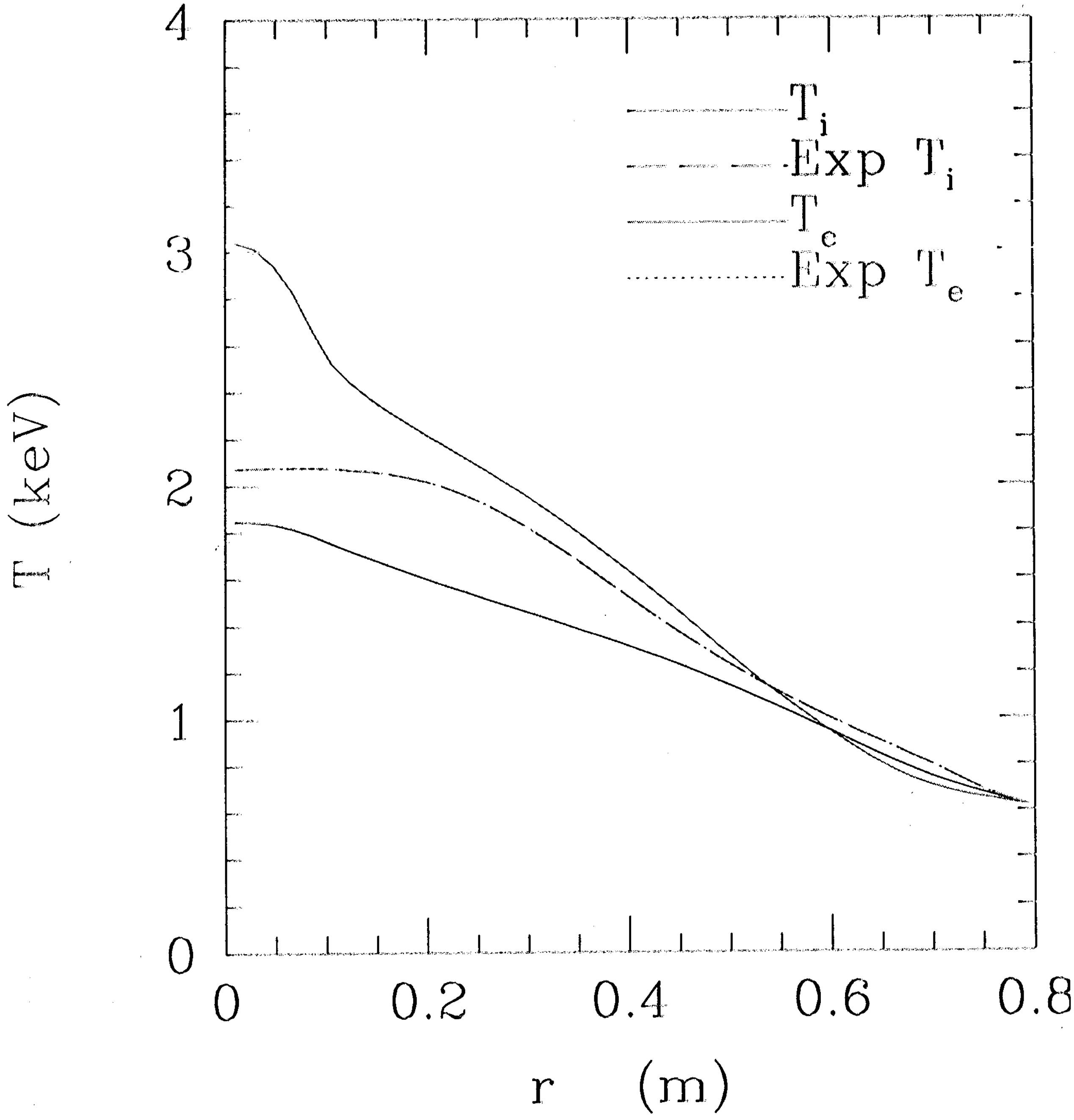
and using the Hahm-Burrell general geometry expression for the shearing rate

$$\gamma_{E\times B} \approx \frac{\kappa}{(1-\Delta')^2} \frac{r}{q} \frac{\partial}{\partial r} \left(\frac{v_\phi}{R}\right)$$

(The theory curves are plotted from the $q = 1$ surface to $r/a = 0.8$.)

33171 w/s

with sheared flow stabilization

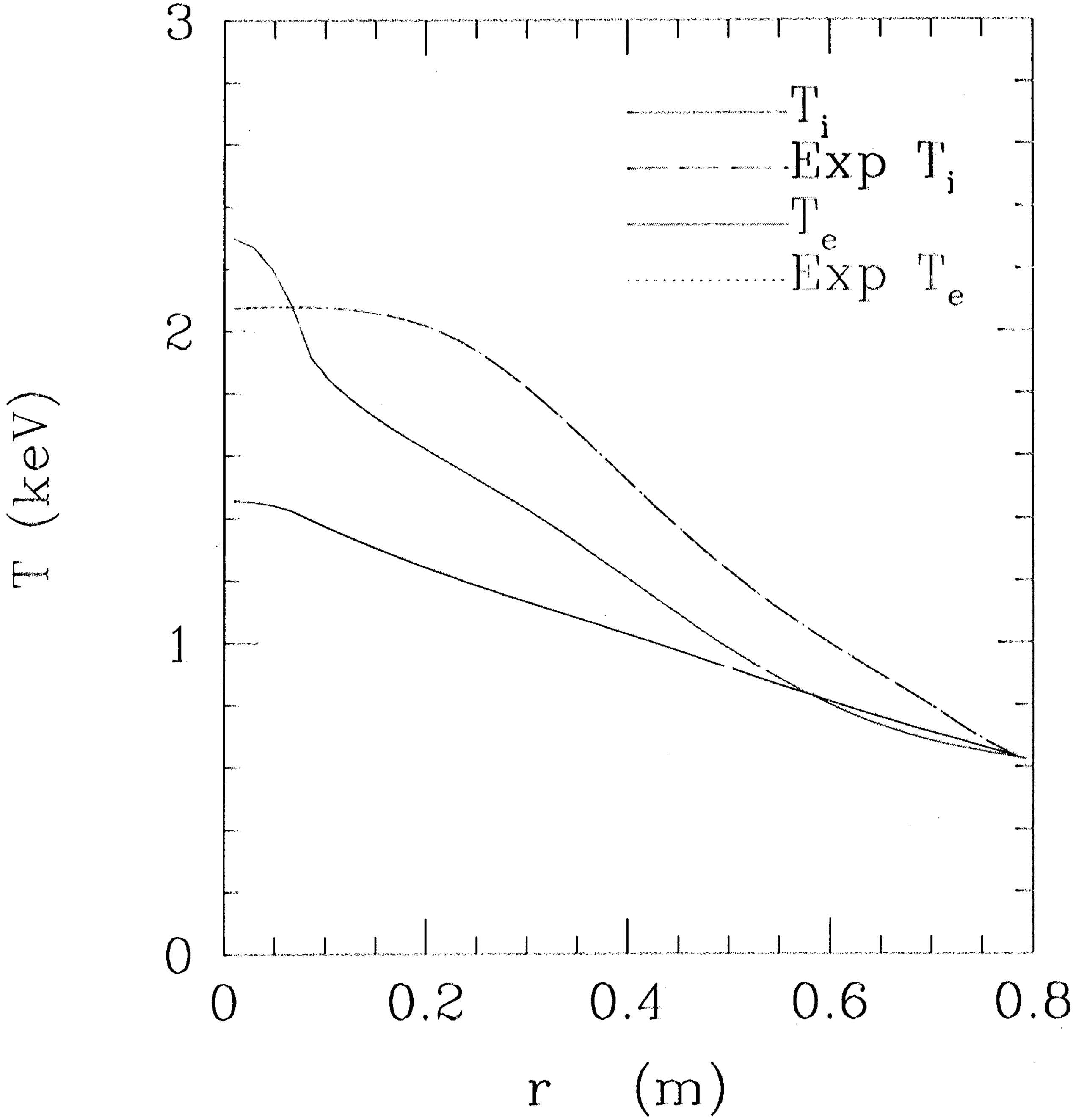


JET H-mode ITER Demo ρ^* Scaling

5171 w/o shear

Ignoring sheared flow effects leads to significantly lower predicted temperatures.

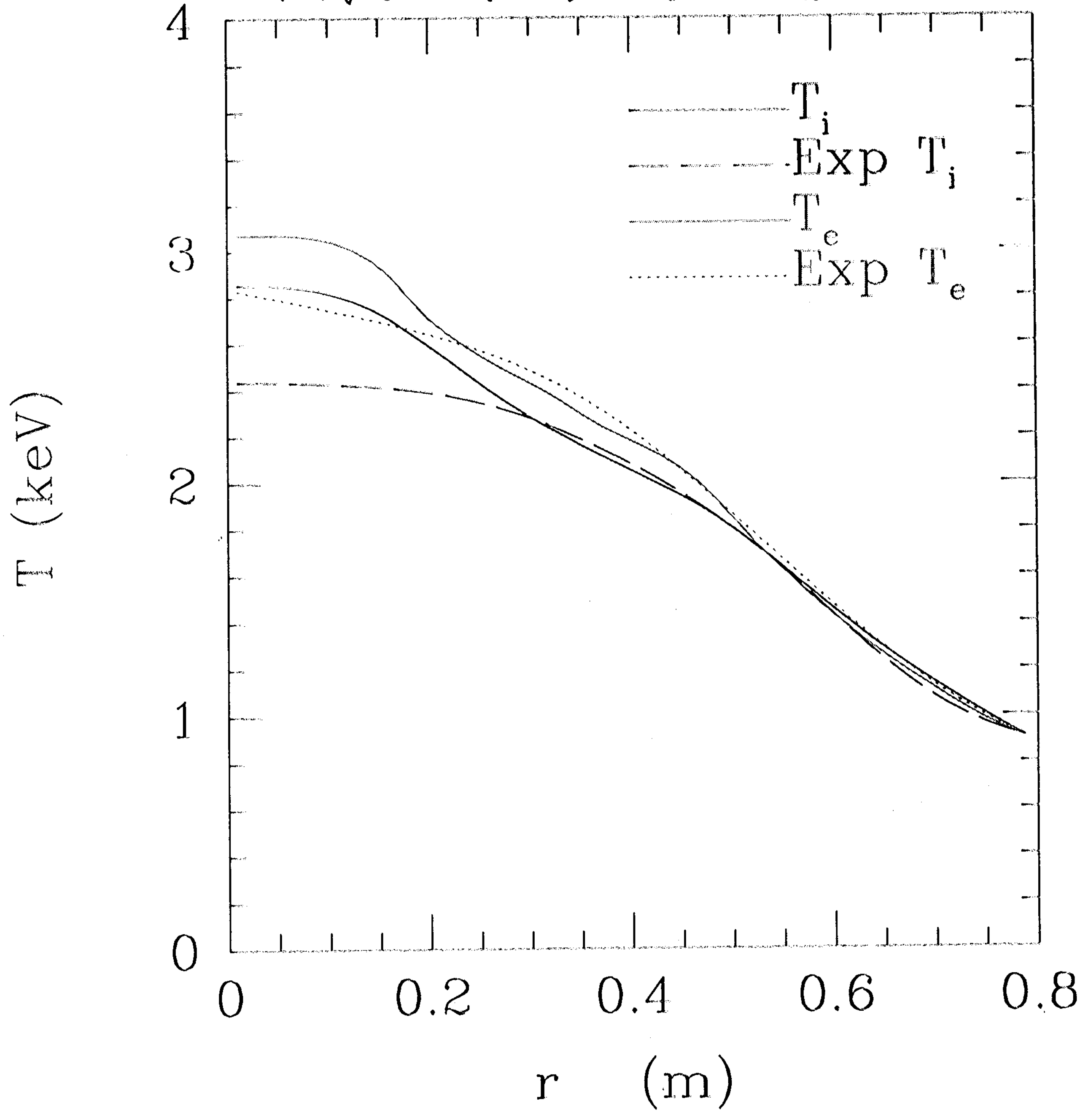
without s.f.s.



JET H-mode ITER Demo ρ* Scaling

35156 w/Shen

With sheared flow stabilization

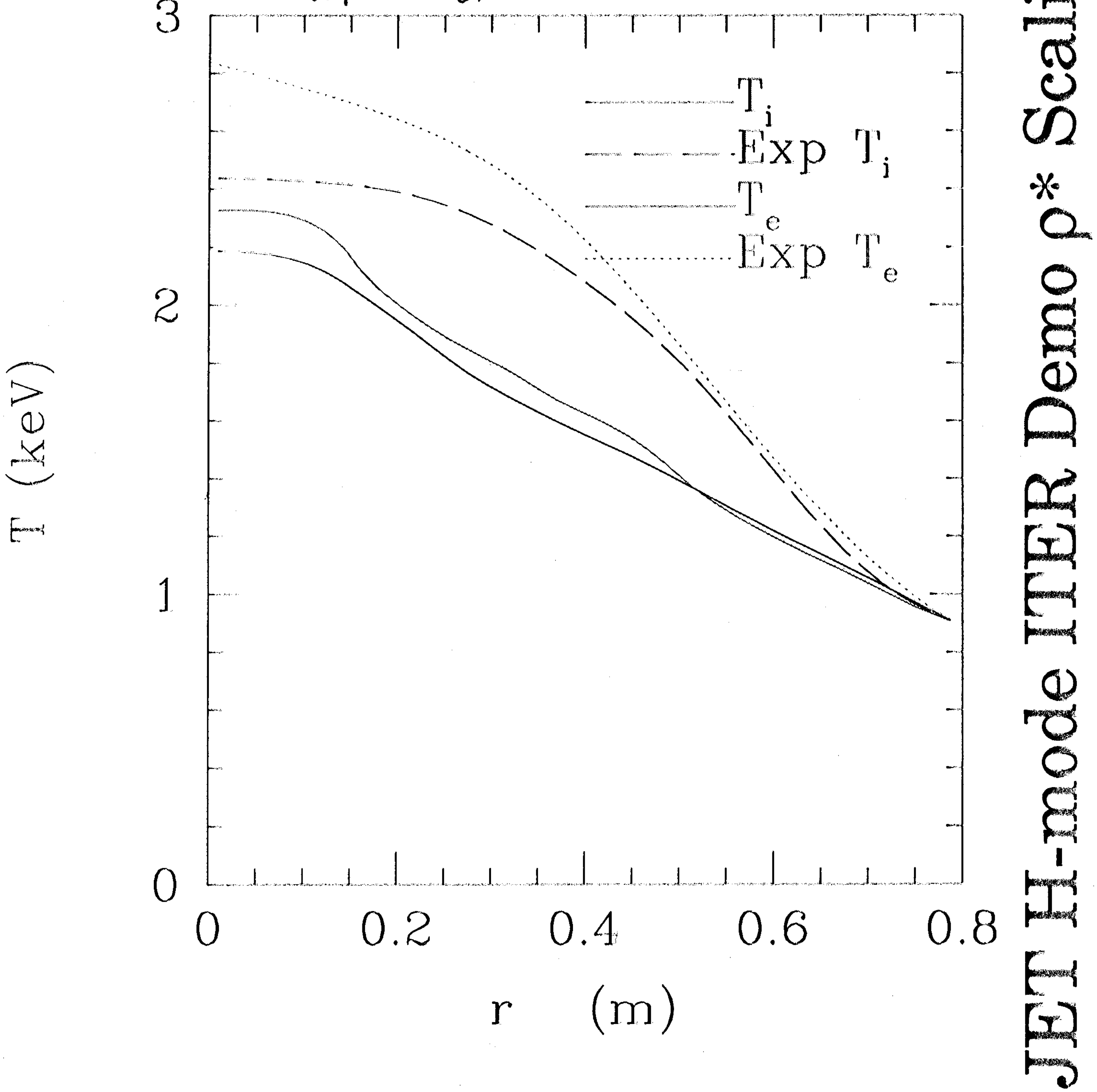


JET H-mode ITER Demo ρ* Scaling

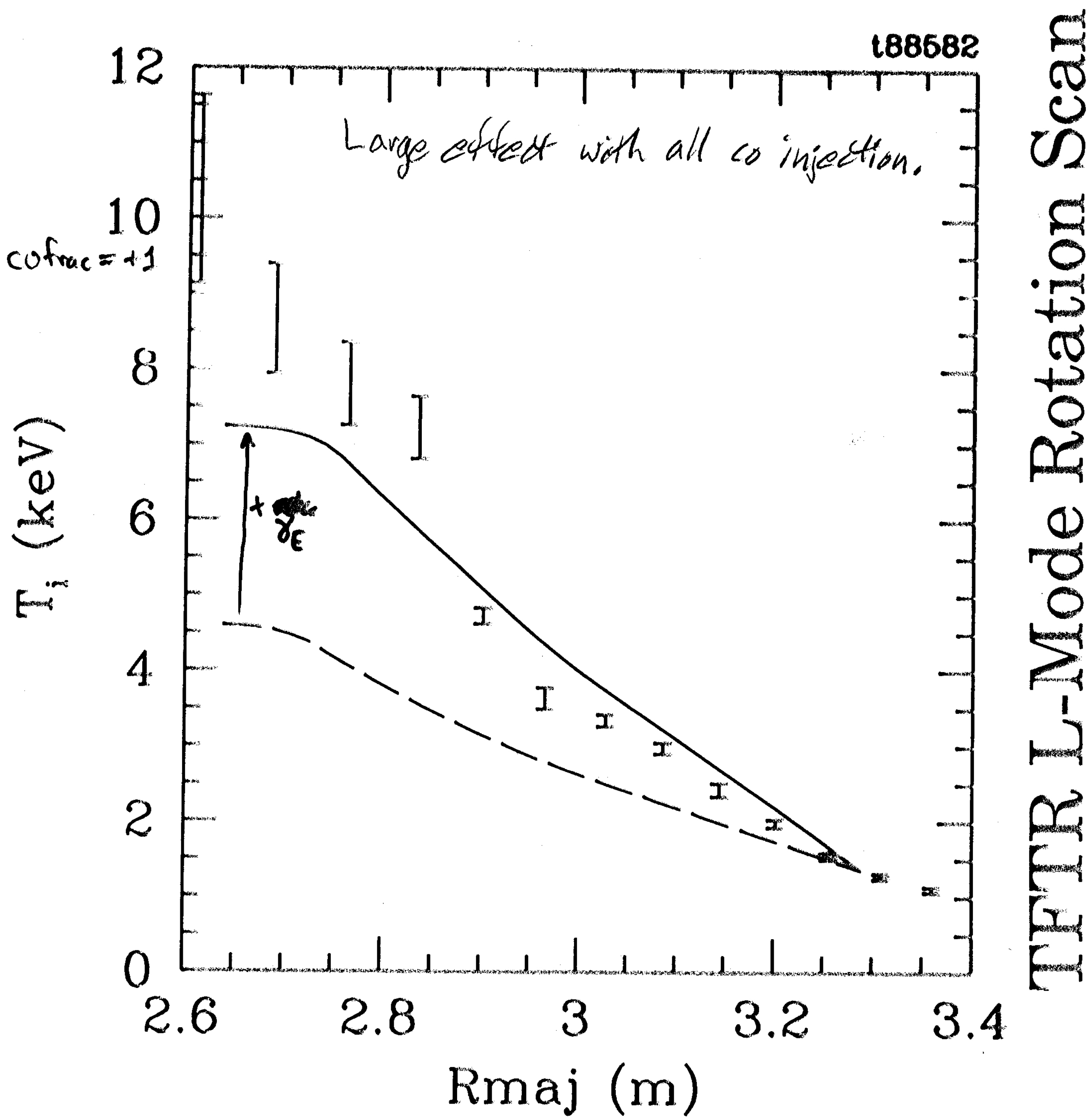
35156 w/o shear

Sheared flow effects are significant for the other paired shot as well.

without s.f.s.

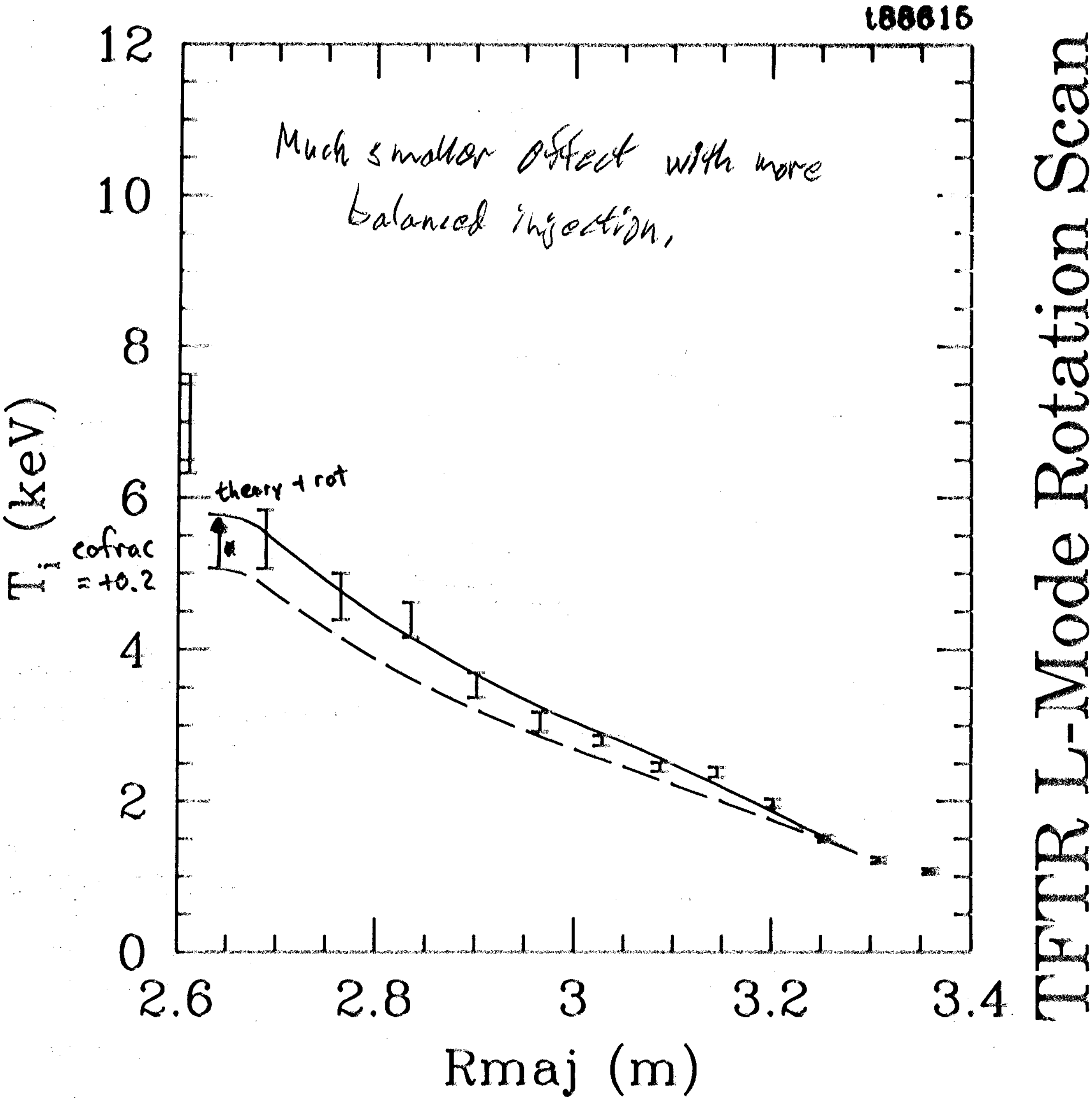


$$\chi_i = \chi_{IFS\text{-}PPL}\left(1-\frac{\gamma_{E\times B}}{\gamma_{lin}}\right)$$

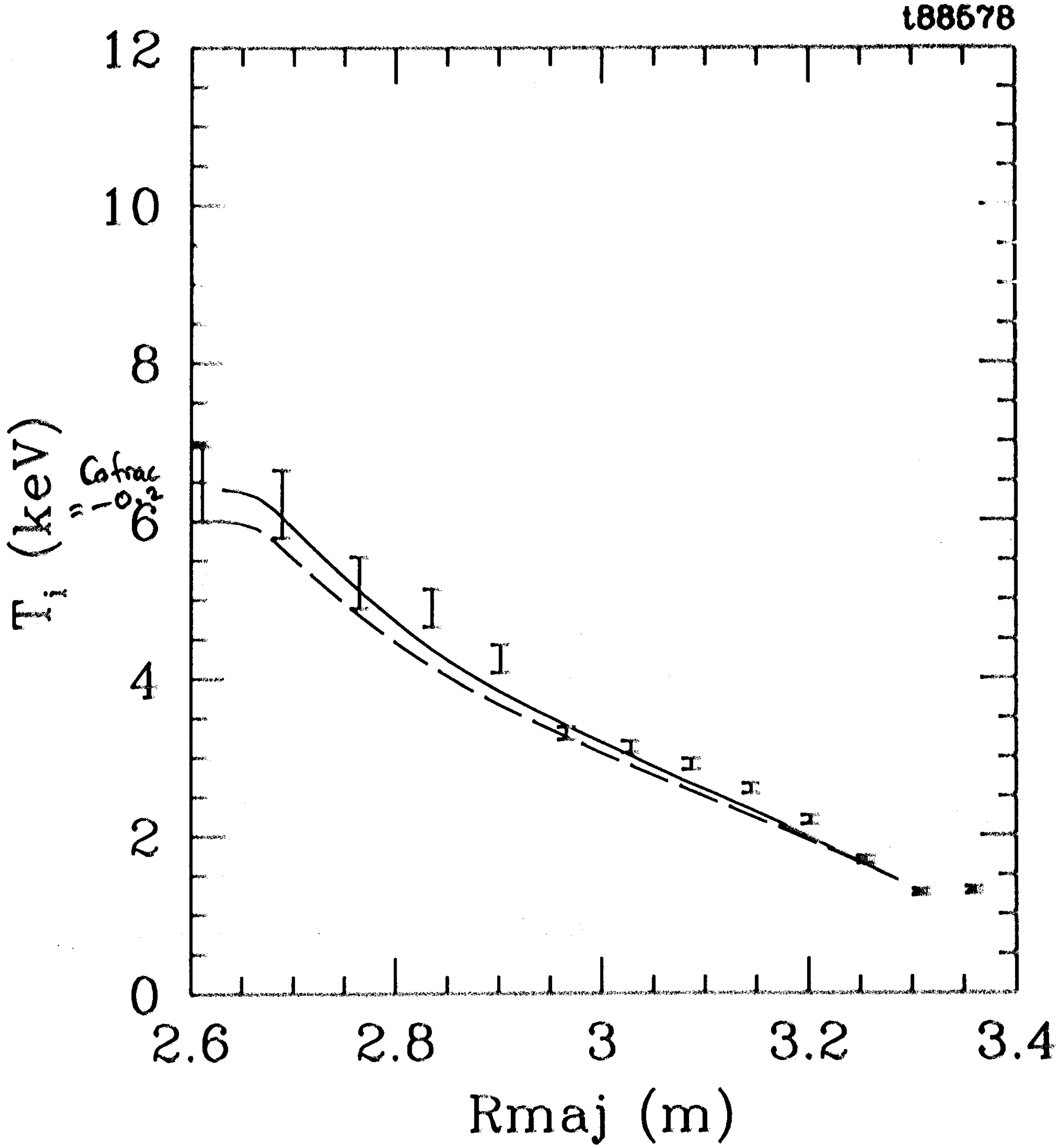


Controlled rotation scan in TFTR

Now using Houlberg complete neoclassical calculation of E_r, for TFTR data, + the Hahm-Burrell gen'l geometry expression for the shearing rate.

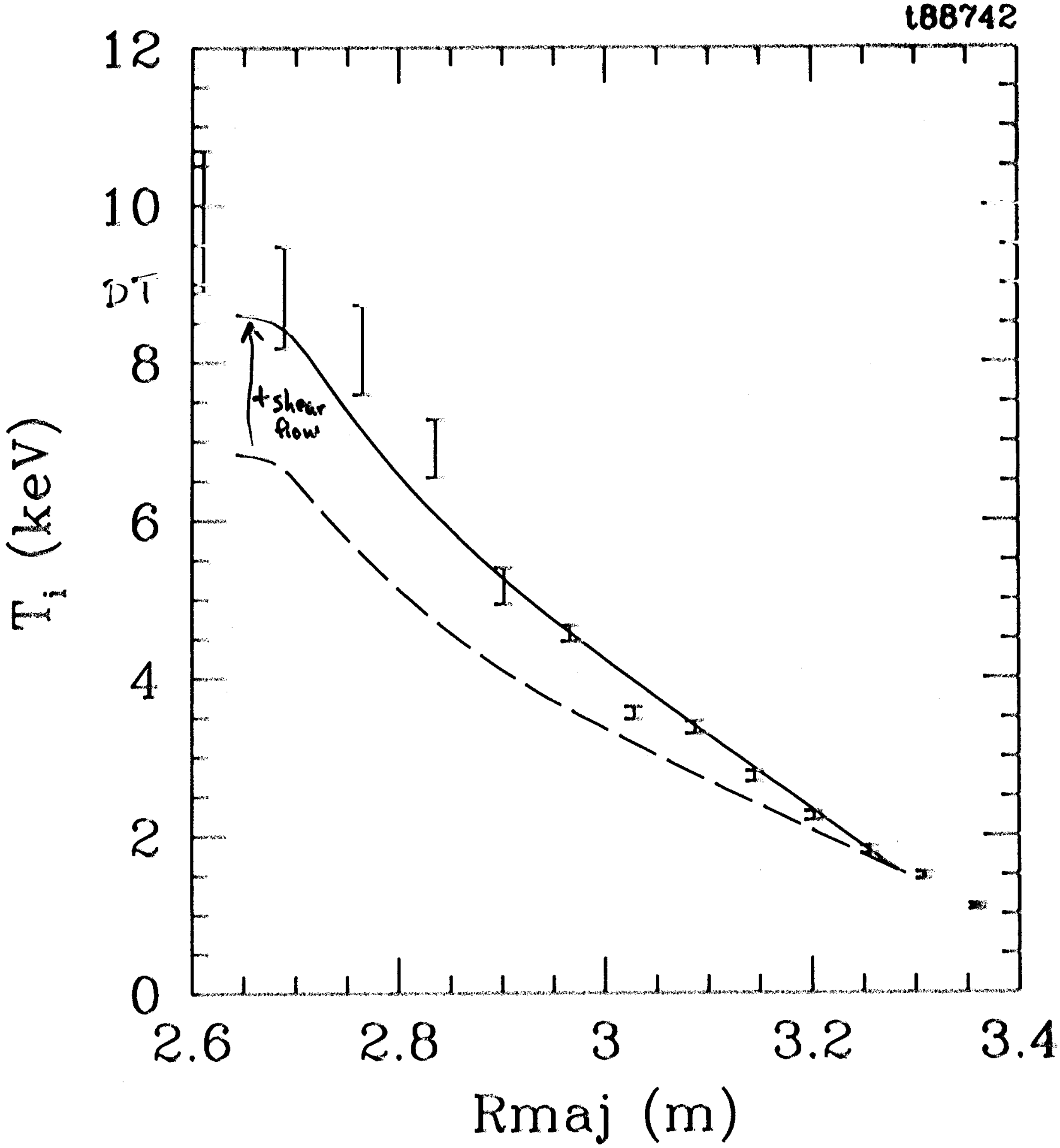


TFTR L-Mode Rotation Scan
t88615
Much smaller effect with more balanced injection.
theory + rot
cofrac = +0.2
T_i (keV)
Rmaj (m)
0
2
4
6
8
10
12
2.6
2.8
3
3.2
3.4

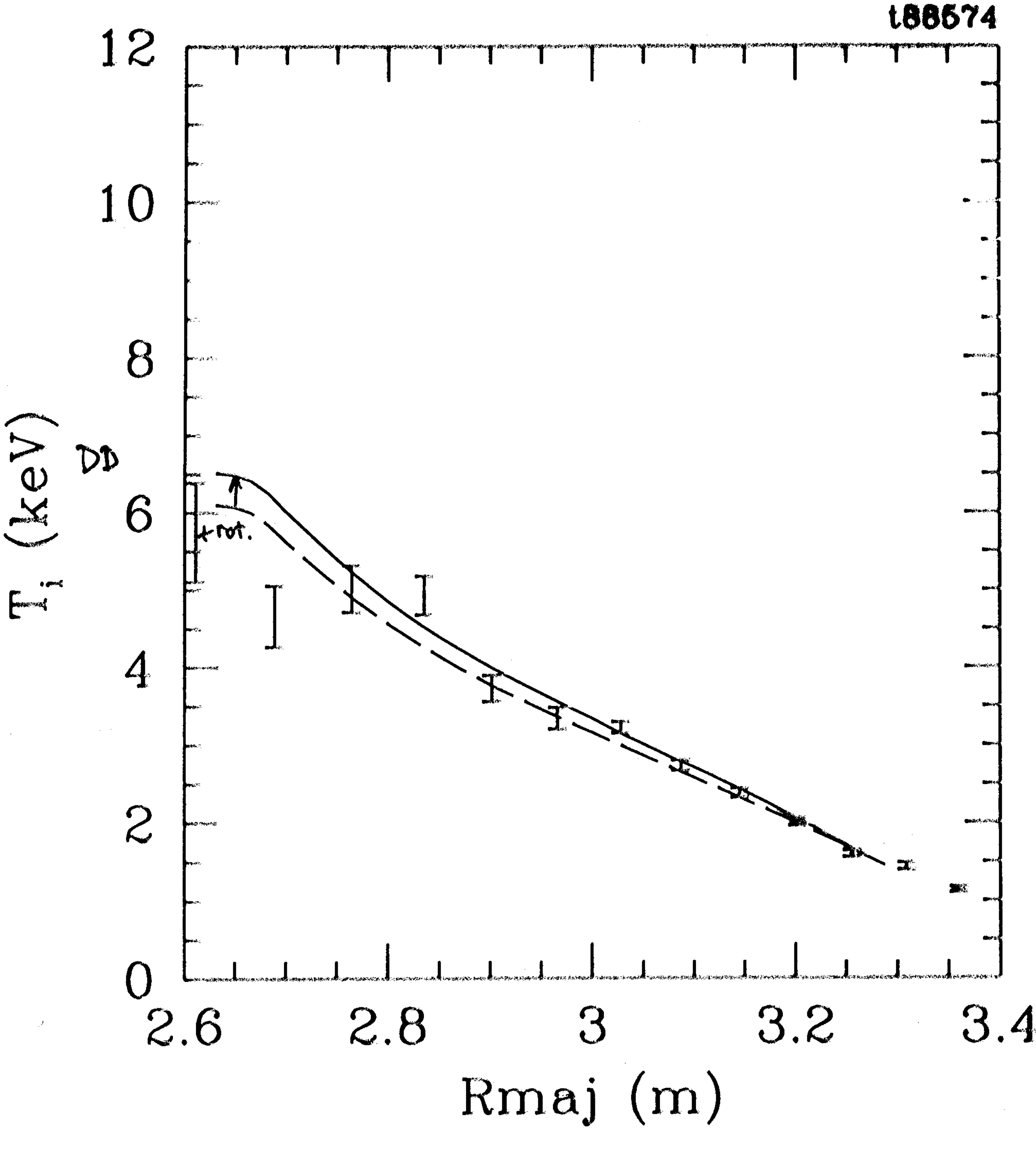


TFTR L-Mode Rotation Scan

Sheared flow effects are stronger in the DT discharge than in the DD comparison with matched P_b.

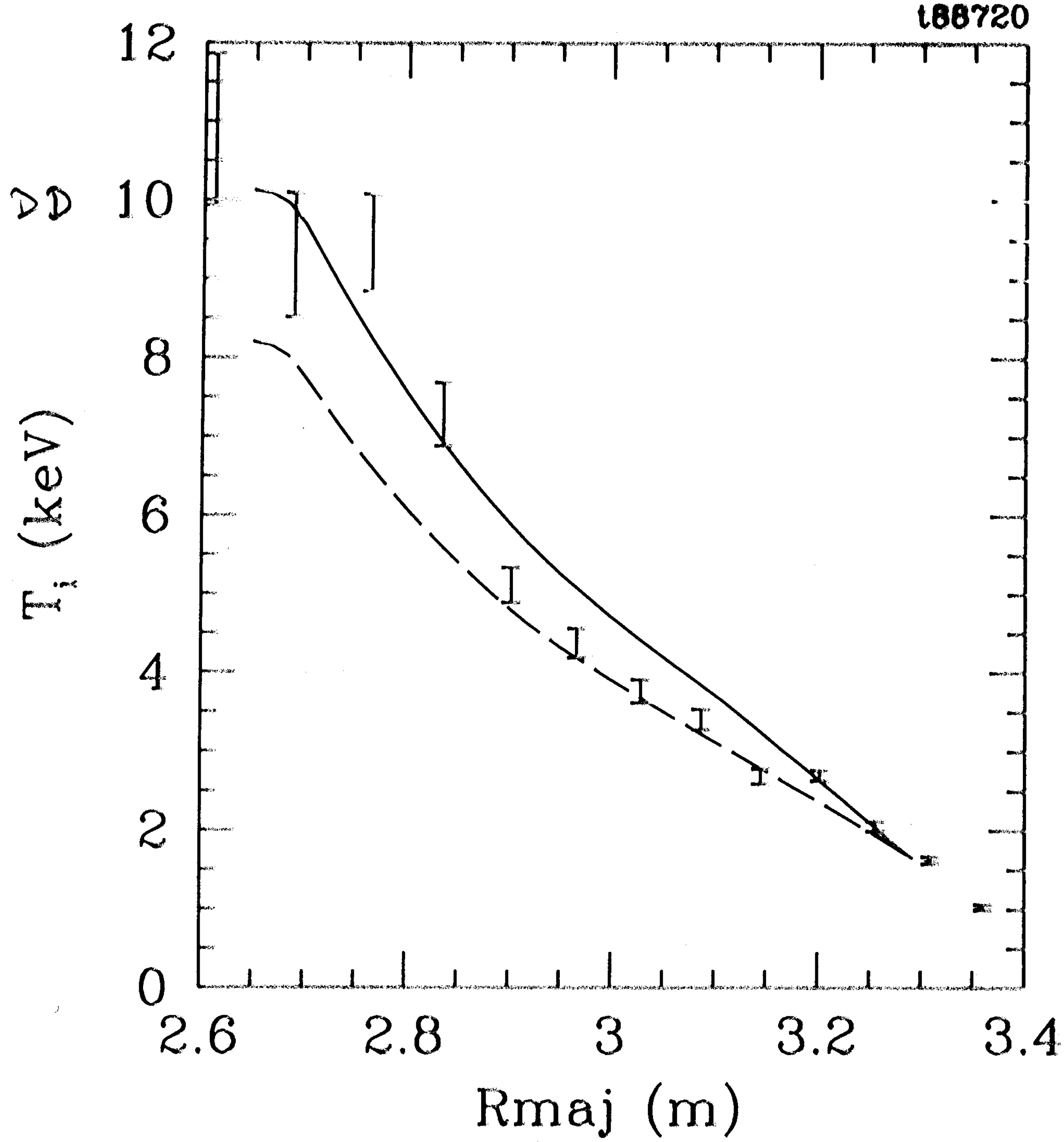


TFTR L-Mode D-T Isotope Scaling



TFTR L-Mode D-T Isotope Scaling

this DD discharge is not well predicted with or without s.f.s.

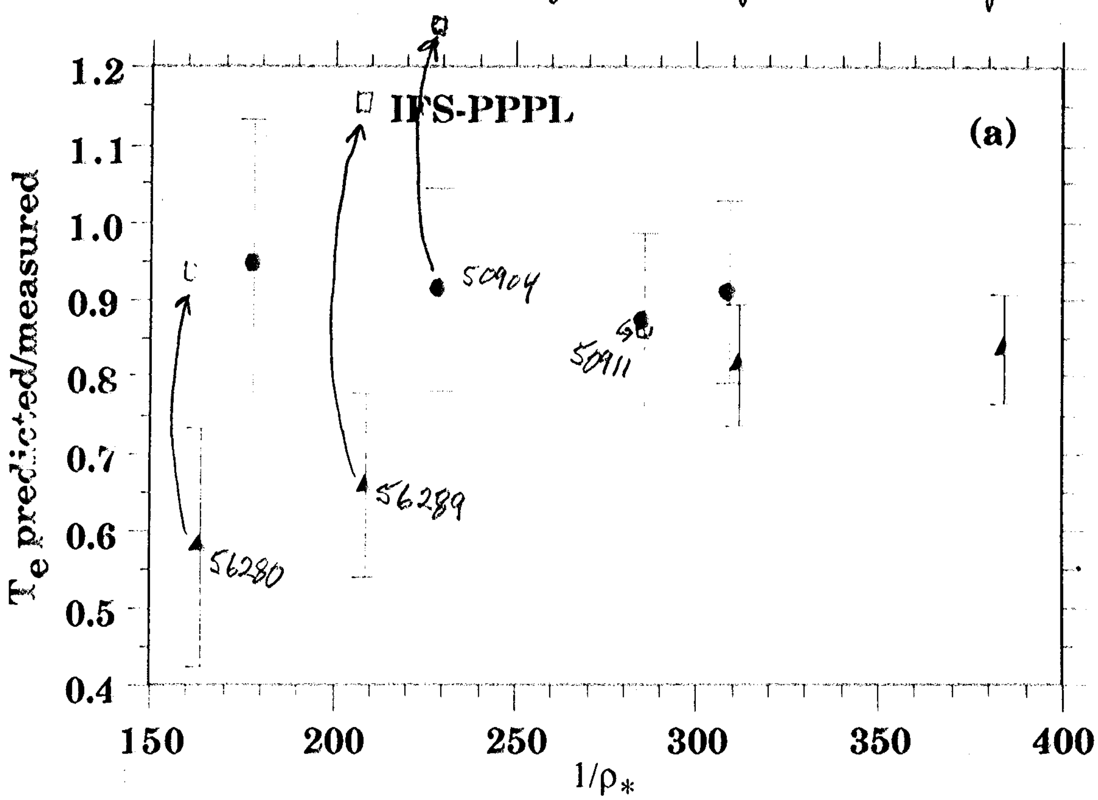


TFTR L-Mode D-T Isotope Scaling

DD with higher power to match DT $T_i(R)$ & $V_\phi(R)$.

TFTR L-Mode ρ* Scaling

sheared flow effects are large for large ρ* discharges



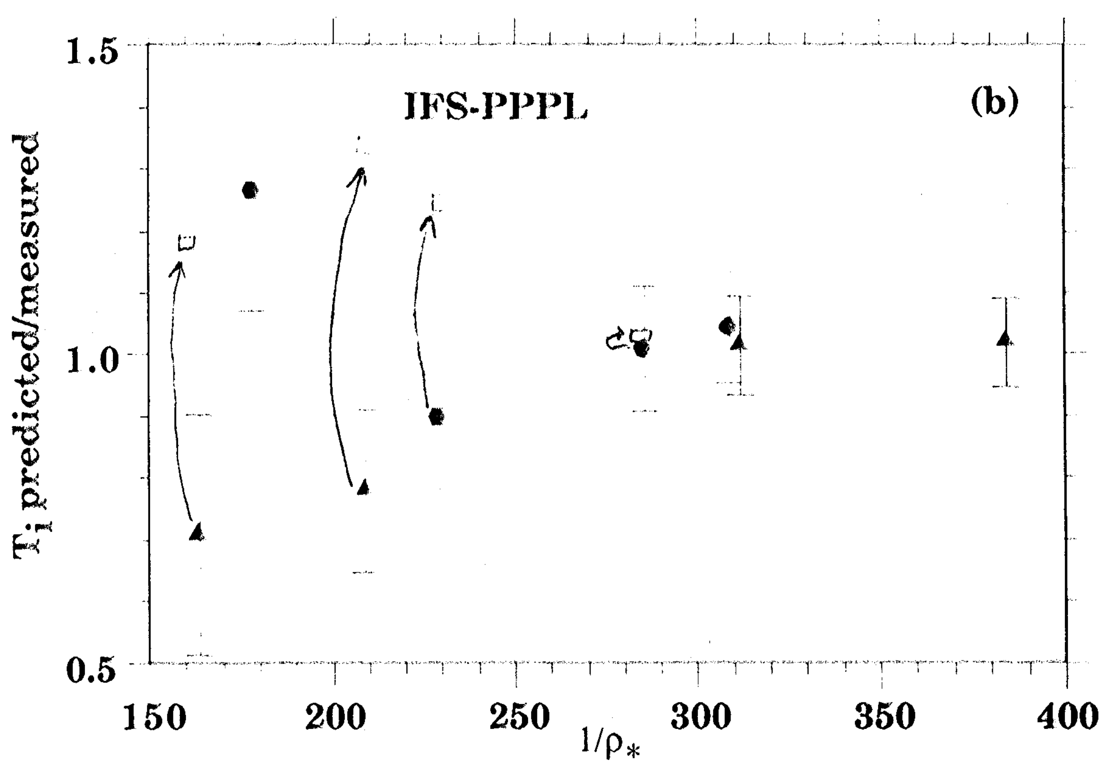


Fig. 6