Study of Critical Pressure Gradient at the Edge of Type I ELMy H-mode plasmas

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Objectives

- **Examine approaches for determining magnetic shear and safety factor used in a prediction of T_{ped}**
- **Examine sensitivity of T_{ped} on the functional form assumed for the elongation and triangularity**
- **Investigate conditions for possible access to 2^{nd} stability of the ballooning mode instability**
- **Simulation of a ρ* scan utilizing a predictive pedestal temperature model in the BALDUR integrated predictive transport code**

Influence of s and q on T_{ped}

- The pedestal width, based on magnetic and flow shear stabilization ($\Delta \propto \rho s^2$), yields:

$$T_{\text{ped}}\,[\text{keV}] = C_w^2\,(3.231\times 10^{37})\left(\frac{B^2}{q^4}\right)\left(\frac{A_H}{R^2}\right)\left(\frac{\alpha_c^2}{n_{\text{ped}}^2}\right)s^4$$

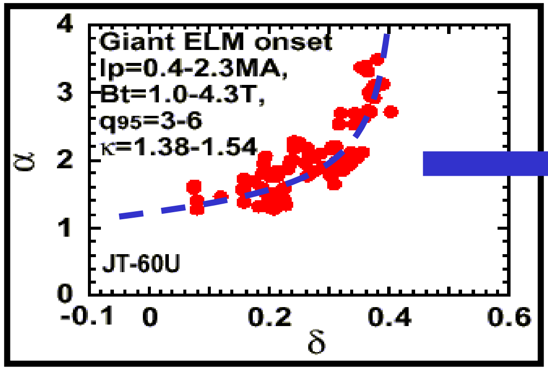
- C_w is a constant in the pedestal width model
- Pedestal temperature is strongly dependent on magnetic shear, s, and safety factor, q
- Equation for T_{ped} may be nonlinear depending on how s and q are computed

Scaling of α_c

- **Normalized critical pressure gradient, α_c, depends not only on magnetic shear, s, but also on a geometrical factor, $f(\kappa,\delta)$**

We express α_c in terms of s and f using: $\alpha_c = 0.8\, s\; f(\kappa,\delta)$

Experimental Suggestion for Geometrical Factor



(Y.Kamada, et al., IAEA 1996)

One approximation considered for the geometrical factor f has the following dependence on elongation and triangularity:

$$f(\kappa,\delta) = 0.5(1+\kappa_{95}^2(1+C_0\delta_{95}^2))$$

We use : $\alpha_c = 0.4\, s\,(1+\kappa_{95}^2(1+C_0\delta_{95}^2))$

Calculation of *s* and *q* using Approach 1

- **Several approaches are proposed to calculate magnetic shear (*s*) and safety factor (*q*)**

Approach 1: Magnetic shear is assumed to be a constant and safety factor is calculated at the 95% flux surface

$$s = 2$$

q_{95} obtained from D. P. Stoler, et al., Comp. Phys. Comm. 81, 261 (1994)

$$q_{95} = \frac{5a^2 B}{IR}\frac{(1+\kappa_{95}^2(1+2\delta_{95}^2-1.2\delta_{95}^3))(1.17-0.65\varepsilon)}{2(1-\varepsilon^2)^2}$$

Calculation of *s* and *q* using Approach 2

Approach 2: **Magnetic shear (*s*) is calculated with bootstrap current effect included. Safety factor is calculated at 95% flux surface.**

$$s = \frac{2\sqrt{\varepsilon}}{\sqrt{\varepsilon} + 0.2 b(\upsilon^*, \varepsilon) f(\kappa, \delta)}$$

$$q_{95} = \frac{5a^2 B}{IR} \frac{(1+\kappa_{95}^2(1+2\delta_{95}^2 - 1.2\delta_{95}^3))(1.17-0.65\varepsilon)}{2(1-\varepsilon^2)^2}$$

Derivation of *s* is shown in A. H. Kritz's poster

Calculation of *s* and *q* using Approach 3

Approach 3: **Magnetic shear and safety factor are calculated at one pedestal width away from the separatrix**

(M. Sugihara, Nuclear Fusion, 40 (2000) 1743)

$$\Delta = a(1-x) = \text{Pedestal width}$$

$$q(x) = \frac{q_{95}}{2.933}\left[\left(1+\left[\frac{x}{1.4}\right]^2\right)^2 + 0.267\left|\ln(1-x)\right|\right]$$

$$s = \frac{x}{q}\frac{\partial q}{\partial x}$$

Calculation of *s* and *q* using Approach 4

Approach 4: Magnetic shear with bootstrap current included and safety factor calculated one pedestal width away from separatrix

$$\Delta = a(1-x) = \textbf{Pedestal width}$$

$$q(x) = \frac{q_{95}}{2.933}\left[\left(1+\left[\frac{x}{1.4}\right]^2\right)^2 + 0.267\left|\ln(1-x)\right|\right]$$

$$s = \frac{s_0\sqrt{\varepsilon}}{\sqrt{\varepsilon} + 0.1 s_0 b(\upsilon^*, \varepsilon) f(\kappa, \delta)} \qquad s_0 = \frac{x}{q}\frac{\partial q}{\partial x}$$

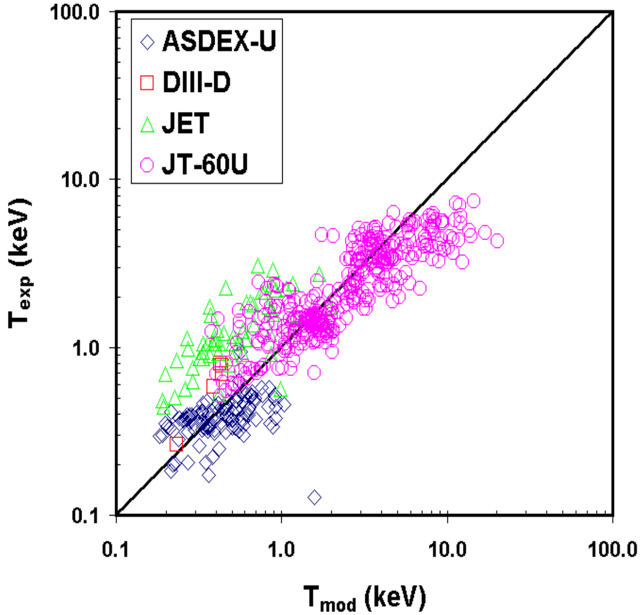
This Approach used in A.H. Kritz and G. Bateman's poster

Result of Approach 1

- The predictions of T_{ped} using Approach 1 compared with 533 experimental data points.

  - Shear is constant (s = 2) and $q = q_{95}$

C_0	RMSE(%)
2.0	57.8
5.0	52.0
10.0	50.7
20.0	60.5

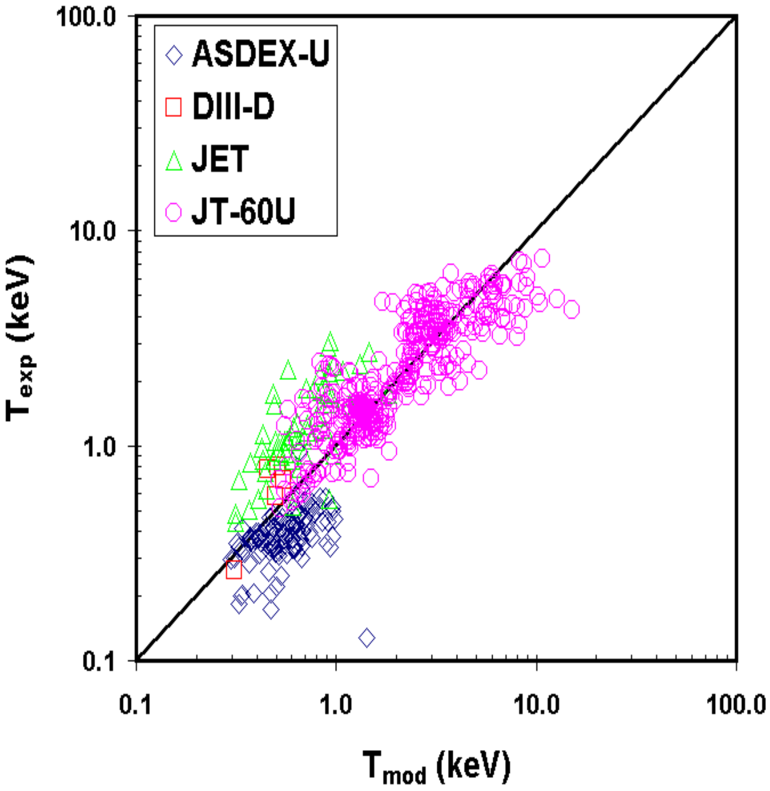


$$f(\kappa,\delta) = 0.5(1+\kappa_{95}^2(1+C_0\delta_{95}^2))$$

Result of Approach 2

➢ **Magnetic shear with bootstrap current and $q = q_{95}$**

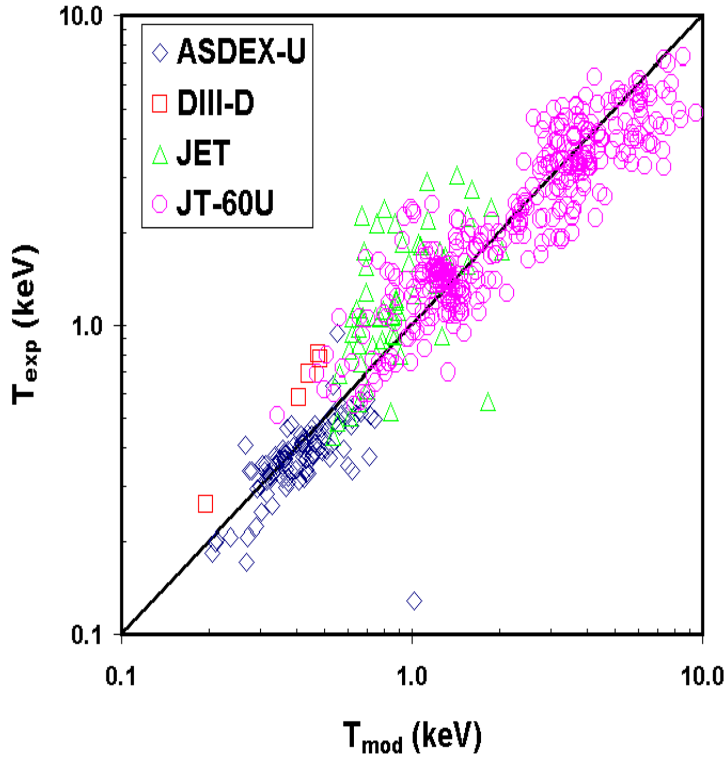
C_0	RMSE(%)
2.0	47.5
5.0	43.3
10.0	40.2
20.0	38.7



Result of Approach 3

➢ ***s*** **and *q* calculated one pedestal width away from the separatrix and bootstrap current effect not included**

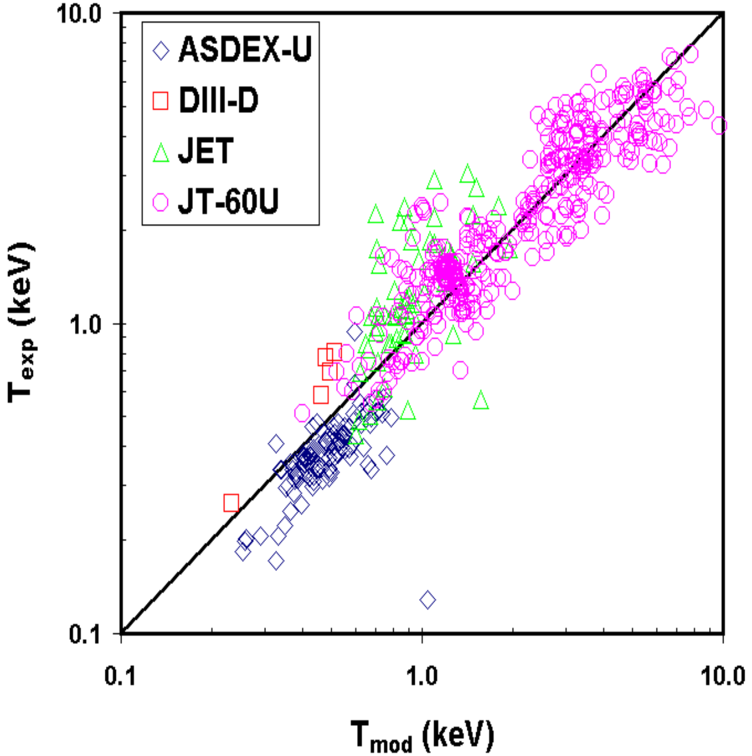
C_0	RMSE(%)
2.0	36.7
5.0	32.2
10.0	29.7
20.0	32.9



Result of Approach 4

➢ *s* with bootstrap current effect included and *q* are calculated one pedestal away from separatrix

C_0	RMSE(%)
2.0	35.4
5.0	32.0
10.0	29.6
20.0	29.0



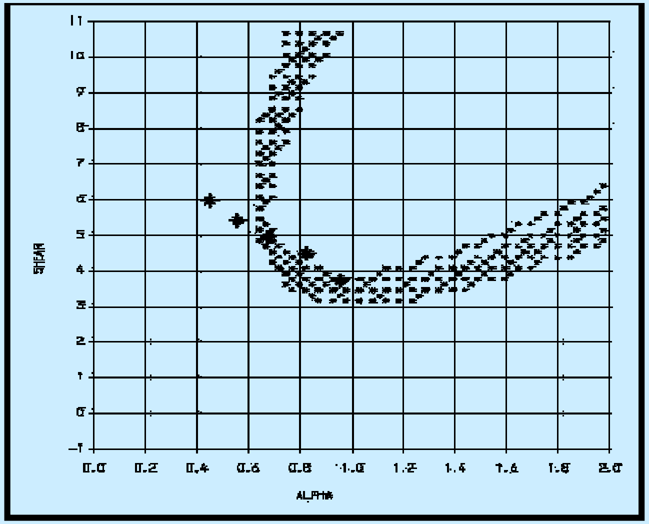
RMS of different approaches for *s* and *q*

- Predictions of pedestal temperature based on different approaches for s and q is compared with 533 experimental data points

	$C_0 = 2$	$C_0 = 5$	$C_0 = 10$	$C_0 = 20$
Approach 1	57.8	52.0	50.7	60.5
Approach 2	47.5	43.3	40.2	38.7
Approach 3	36.7	32.2	29.7	32.9
Approach 4	35.4	32.0	29.6	29.0

Access to 2nd stability

Evolution of pressure gradient at 95% flux surface

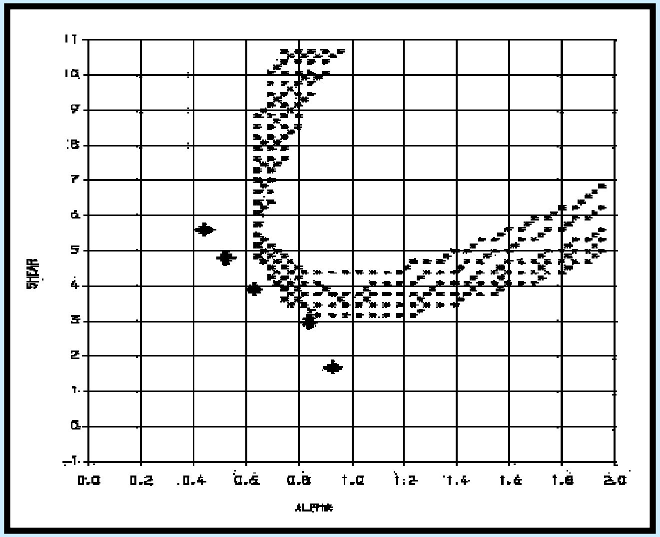


- **JET Discharge 53186 (low triangularity) does not have access to 2nd stability**
  - **Enter unstable regime of ballooning mode**
  - **Remains at the transition between 1st and 2nd stability (at the nose of unstable curve)**

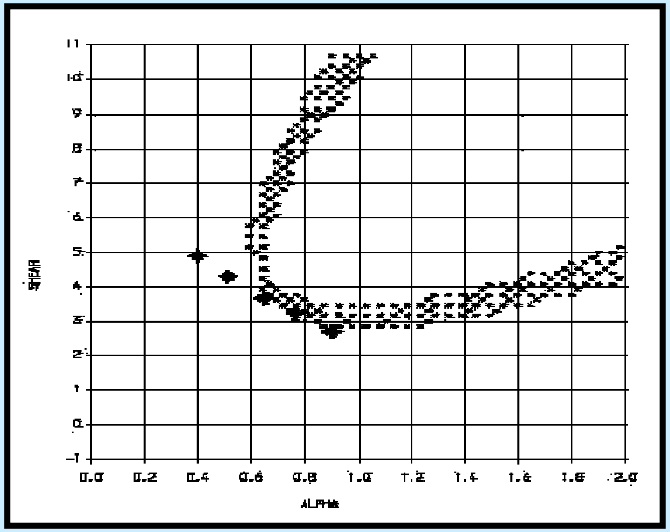
- **Possible access to 2nd stability can be achieved by**
  - **Strong shaping (high triangularity)**
  - **Strong edge current**
    - **achieved by increasing bootstrap current or**
    - **achieved by increasing plasma current**

Result of Increasing of Edge Current

- Bootstrap current is artificially increased by a factor of 2.



- Ramping current up from 2.5 MA to 3.0 MA during 1 sec.



- **With a small change in the edge conditions, the edge pressure gradient can change dramatically and impact the performance of the plasma in H-mode**
  - **For example, access to 2nd stability can achieved**

Core and Edge model

- Pedestal temperature model is implemented in the predictive integrated transport code, BALDUR, to provide boundary conditions

Core transport model

- Core transport is calculated using MMM95 model
- Agrees with experimental results (within 15% RMS deviation)

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Pedestal temperature model

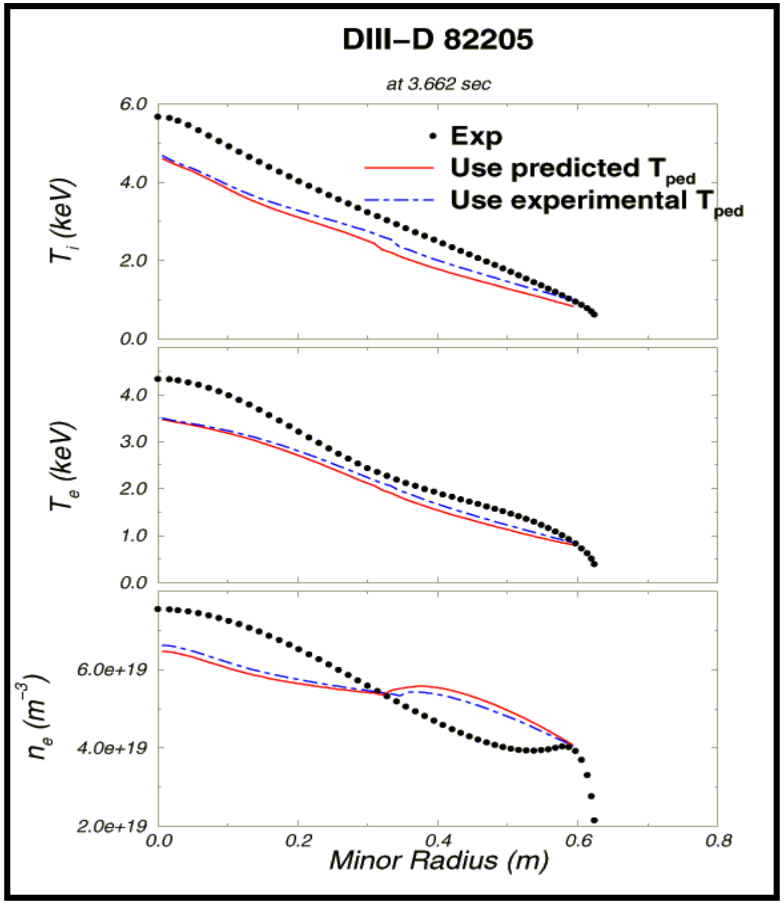
- Based on ballooning mode for pressure gradient (approach 4) and flow&magnetic shear stabilization for width
- Approximately 32% RMS deviation from experimental results

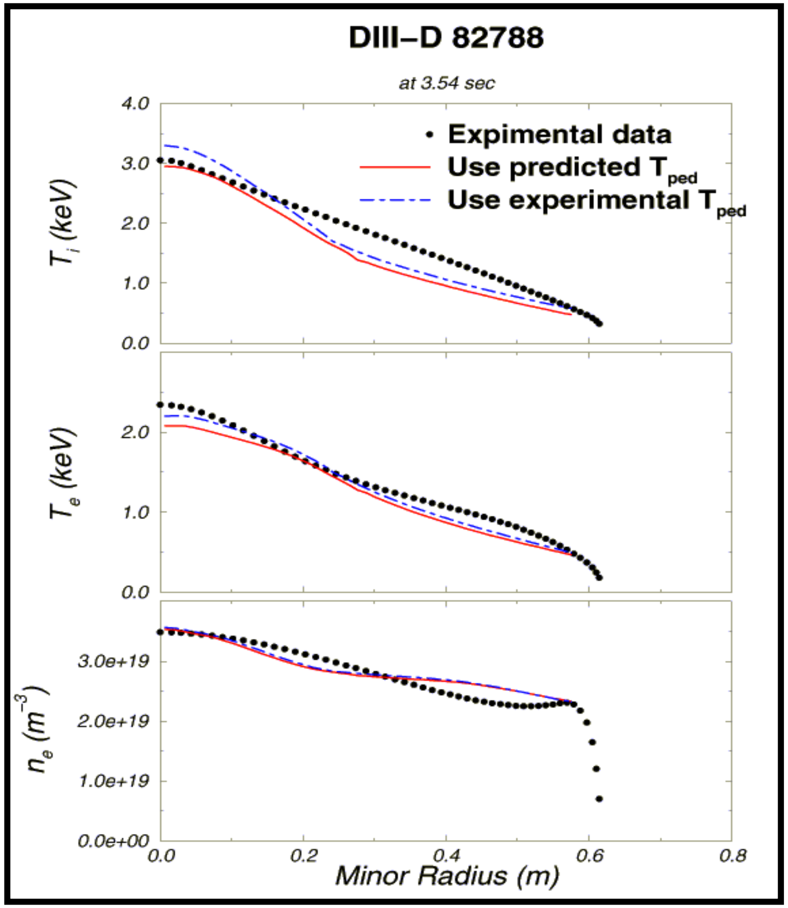
ρ* scan

- **Simulations of ρ* scans in DIII-D and JET have been carried out using BALDUR code**

Discharge	D3D 82205	D3D 82788	JET 33131	JET 33140	JET 35156	JET35171
Type	Low ρ*	High ρ*	Low ρ*	High ρ*	Low ρ*	High ρ*
R (m)	1.69	1.68	2.94	2.93	2.87	2.88
a (m)	0.63	0.62	0.94	0.92	0.93	0.94
I_p (MA)	1.34	0.66	2.83	1.61	2.05	1.01
B (T)	1.87	0.94	3.13	1.77	2.17	1.09
κ	1.71	1.67	1.70	1.56	1.56	1.58
δ	0.37	0.35	0.28	0.26	0.11	0.24
ρ*(0)	0.013	0.019	0.005	0.008	0.005	0.010

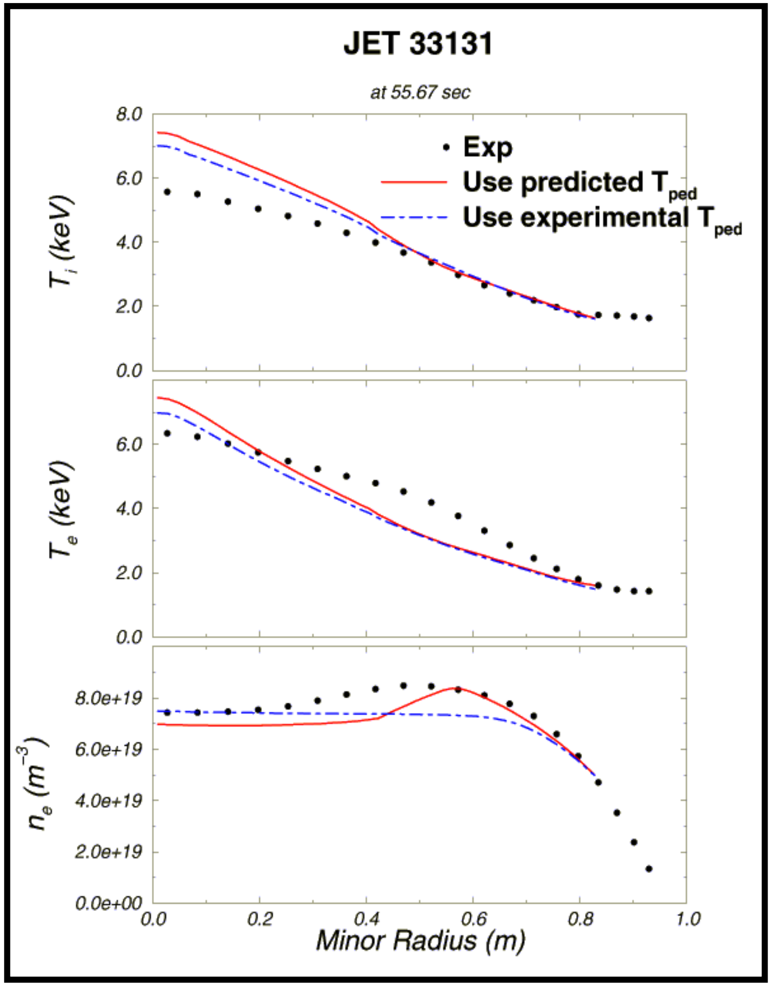
Simulations of ρ* scan in DIII-D

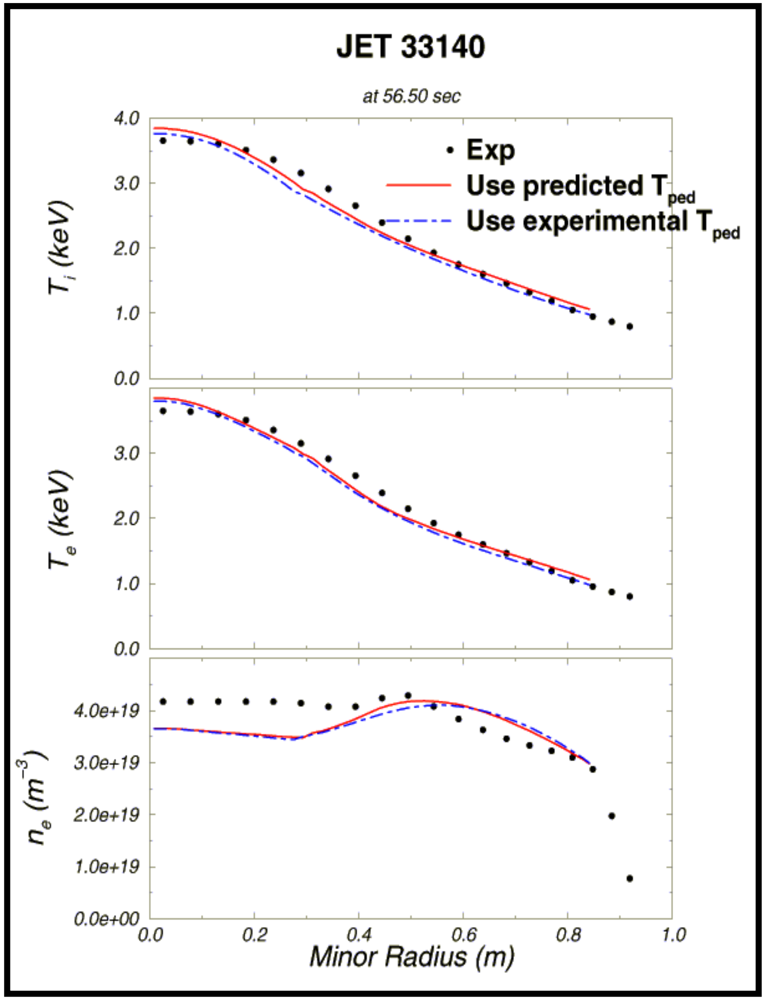




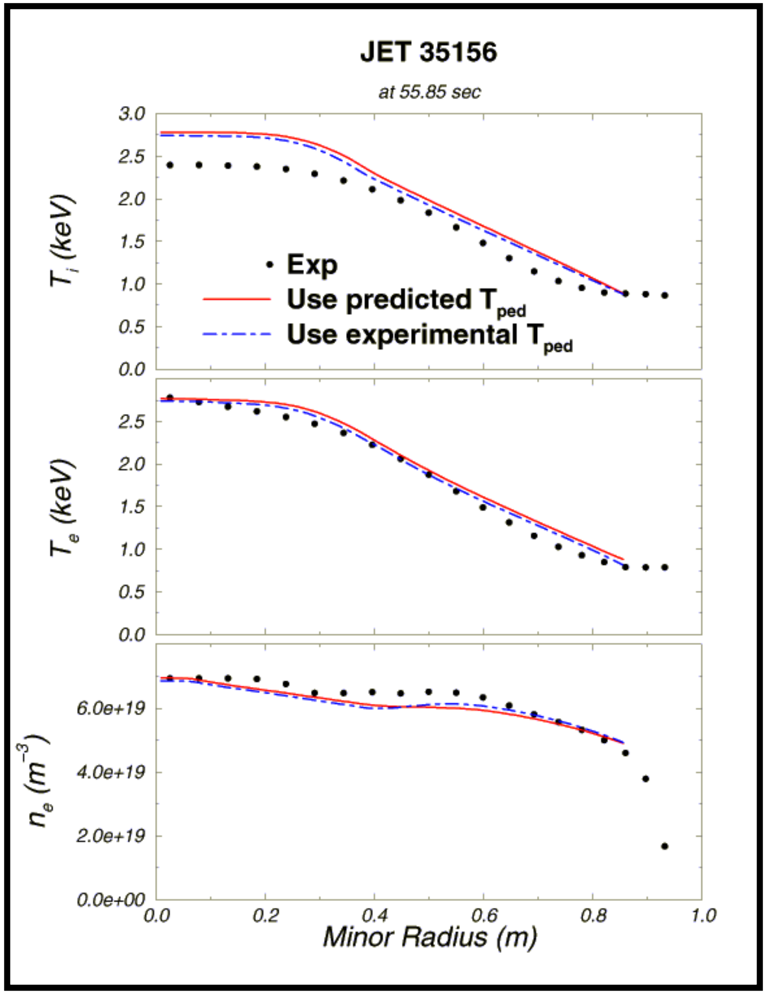
Simulations use MMM95 + $\Delta \propto \rho s^2$ + Approach 4 for *s* and *q*

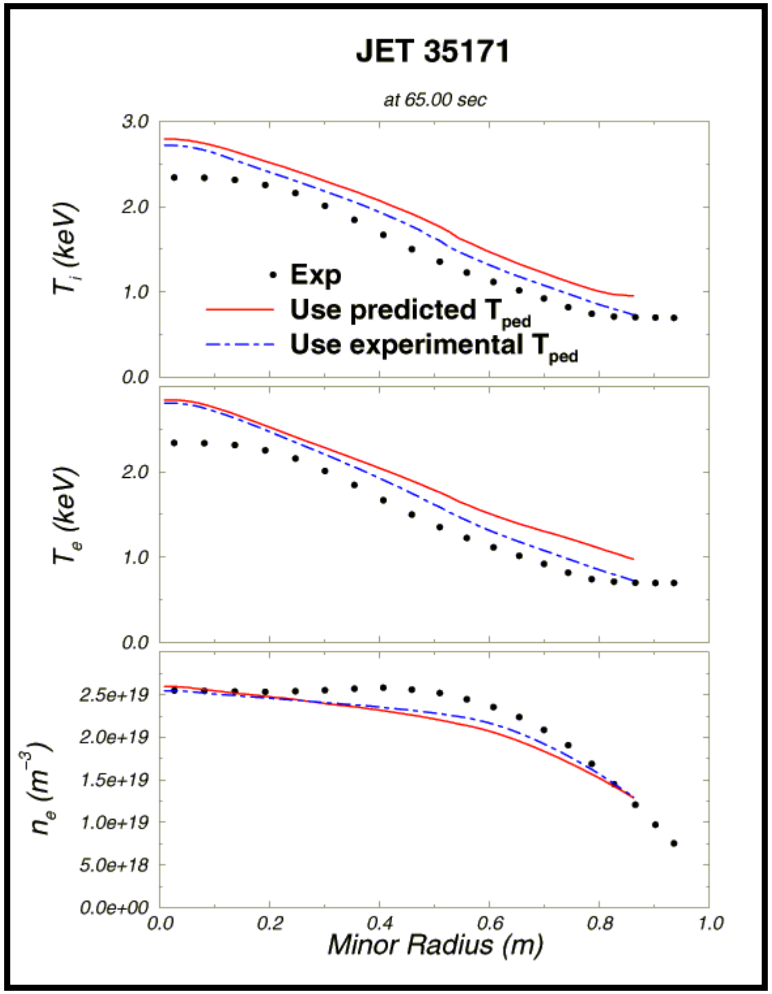
Simulations of ρ∗ scan in JET





Simulations of ρ* scan in JET





Pedestal scaling in ρ* scan

- In ρ* scan, β and ν* are kept constant
  - This results in the relationship $T_{core} \propto B^{0.67}$

Discharge	B (T)	T_{ped} (keV)
DIII-D 82205	1.87	0.79
DIII-D 82788	0.94	0.46
JET 33131	3.13	1.59
JET 33140	1.77	1.04

$$\frac{T_{ped,82205}}{T_{ped,82788}} = \left(\frac{B_{82205}}{B_{82788}}\right)^{0.79}$$

$$\frac{T_{ped,33131}}{T_{ped,33140}} = \left(\frac{B_{33131}}{B_{33140}}\right)^{0.74}$$

- In the pedestal region, $T_{ped} \propto B^{0.77}$
- Stronger temperature dependence on magnetic field in the pedestal than in the core

Summary-1

- **Using *s* at one pedestal width away from the separatrix and modified with bootstrap current (Approach 4) yields lowest RMS error**
  - **29.0 % with the geometrical factor of $f(\kappa,\delta) = 0.4\, s\, (1 + \kappa_{95}^2(1 + 20\delta_{95}^2))$**
- **Increasing effect of triangularity yields better agreement with experimental data**
- **Bootstrap current has limited effect in improving the agreement with data**
  - **Negligible effect when shear is calculated at one pedestal width away from separatrix**

Summary-2

- **Plasma can access 2nd stability with large plasma edge current**
  - **Increase bootstrap current or plasma current**
- **Simulations of ρ* scans discharges carried out using the BALDUR integrated transport code with a predictive boundary model for T_e and T_i**
  - **Errors in the prediction of T_{ped} do not amplify the error in the core predictions**
  - **T_{ped} scales as $B^{0.77}$ in the pedestal region**
    - **T_{ped} has stronger dependence on B than does T_{core}**