Testing H-mode Pedestal and Core Transport Models Using Predictive Integrated Modeling Simulations

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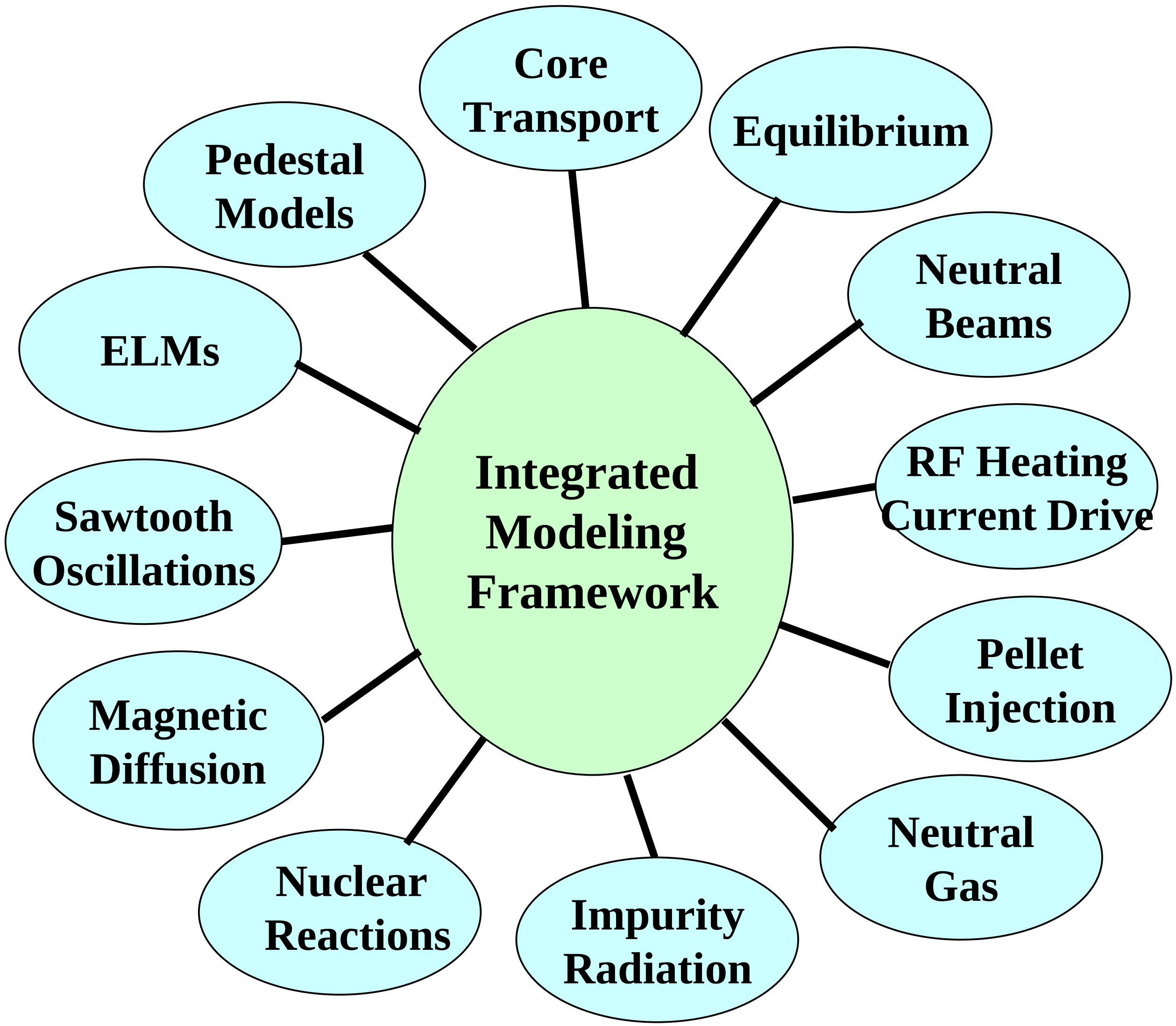
Outline

- **H-mode pedestal models are used together with core plasma models in the BALDUR integrated modeling code**
  - **Integrated predictive simulations compared with experimental data**
  - **Simulations carried out for ITER and FIRE fusion reactor designs**
- **See the adjacent posters by A.H. Kritz and T. Onjun for the development of H-mode pedestal temperature models**
  - **T. Onjun, G. Bateman, A. H. Kritz, and G. Hammett, "Models for the Pedestal Temperature at the Edge of H-mode Tokamak Plasmas" April, 2002.**
- **These models are used in predictive simulations of experimental data to test them in the context of integrated modeling**
- **The pedestal and core models are then use in integrated simulations to predict the performance of the ITER and FIRE fusion reactor designs**

Integrated BALDUR Modeling Code

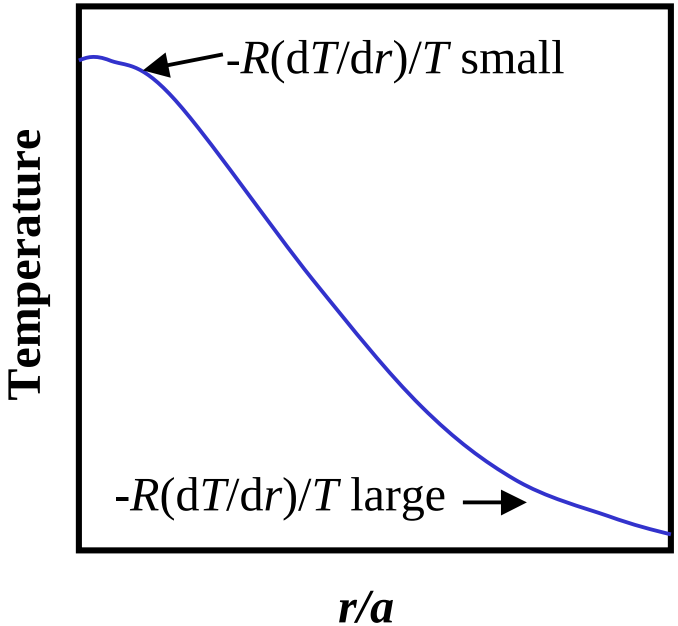


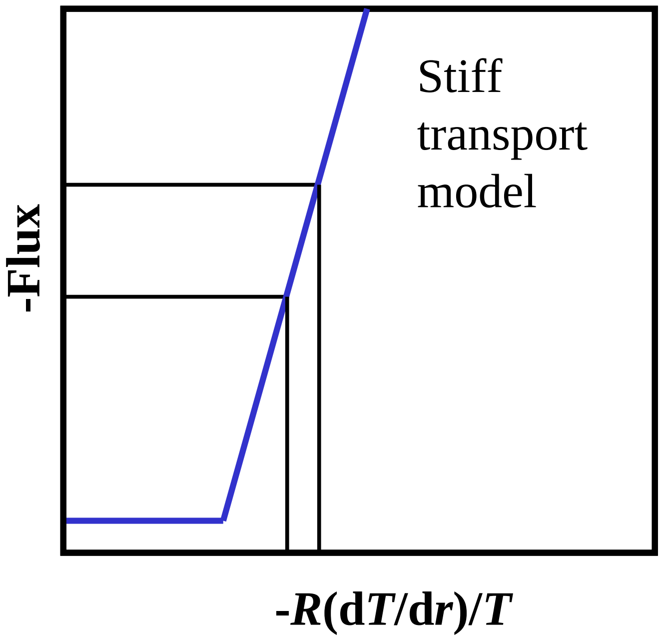
BALDUR Transport Code

- **Predicts time-dependent profiles for**
  - **electron and ion temperature**
  - **each ion density (hydrogenic and impurity)**
  - **magnetic *q*(r,t)**
  - **neutrals**
- **Self-consistent computations of**
  - **sources (such as NBI heating or fusion reactions)**
  - **sinks (such as impurity radiation)**
  - **transport fluxes**
  - **MHD equilibrium**
  - **large scale instabilities (such as sawtooth oscillations)**

Stiff Transport Models

Modern turbulence-driven transport models are stiff





In a stiff transport model, the transport flux increases rapidly with increasing logarithmic temperature gradient, once that temperature gradient rises above a threshold value

Predictive Versus Analysis Codes

Analysis Code

Compute source

Compute heat flux

Compute χ from heat flux
(e.g., χ = - heat flux / $n \nabla T_{exp}$)

Compare χ from heat flux with χ from model

⇑

Compute χ from transport model

⇑

Compute ∇T/T

⇑

Measured T profile

Predictive Code

Compute source

Compute χ from transport model

Advance transport equations and predict T profile

Compare predicted T profile with measured T profile

Testing H-mode Pedestal Model in BALDUR Simulations of Experimental Data

- **The development of our H-mode pedestal temperature models is described in the adjacent posters by A.H. Kritz and T. Onjun**
  - **A model for the H-mode pedestal density is described later in this poster**
- **The H-mode pedestal temperature model is tested here in BALDUR integrated simulations of experimental data**
  - **We used the pedestal model based on $\Delta \propto \rho s^2$ to predict T_{ped}**
  - **The standard Multi-Mode transport model used for core plasma**
  - **Simulations of gyro-radius scans shown in adjacent poster by T. Onjun**
  - **Simulations shown here for scans in power, density, and elongation**
  - **Statistics are used to summarize the results of all 12 simulations**

Objectives of BALDUR Simulations Using Model for T_{ped}

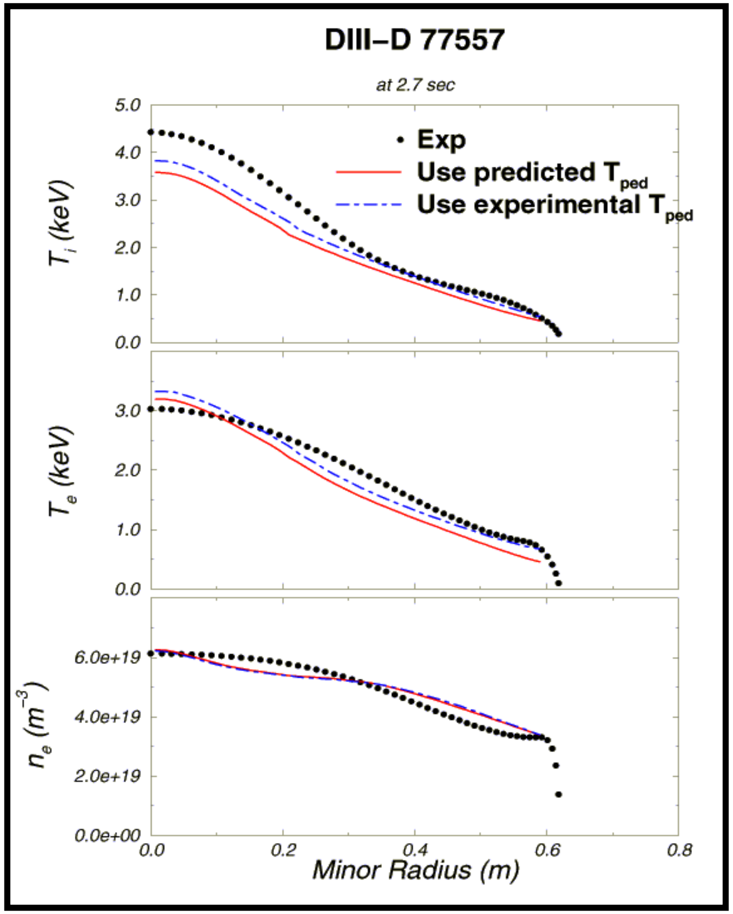
- **Pedestal temperatures and densities are used as boundary conditions in the BALDUR integrated modeling code**
- **In the past, we used experimental data for these pedestal temperatures and densities**
  - **This use of experimental data made the simulations less predictive**
- **In the tests shown below, we use a model to predict T_{ped}**
  - **Simulations using the model for T_{ped} are compared with simulations using experimental data for T_{ped}**
  - **Both simulations are compared with experimental data for the profiles**
  - **Do the errors in the model for T_{ped} amplify or compensate with the errors in the integrated modeling of the core?**

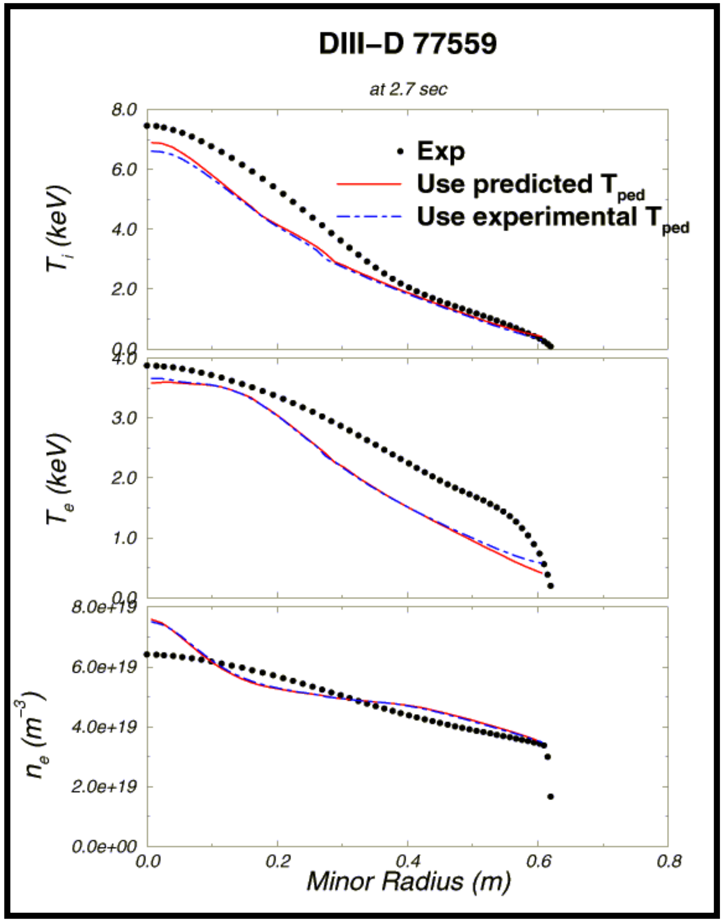
Systematic scans

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

Discharge	D3D 77557	D3D 77559	D3D 81321	D3D 81329	D3D 81499	D3D 81507
Type	Low power	High power	Low n_e	High n_e	Low κ	High κ
R (m)	1.68	1.69	1.69	1.70	1.69	1.61
a (m)	0.62	0.62	0.60	0.59	0.63	0.54
I_p (MA)	1.00	1.00	1.00	1.00	1.35	1.34
B (T)	1.99	1.99	1.98	1.97	1.91	1.91
κ	1.85	1.84	1.83	1.83	1.68	1.95
δ	0.33	0.35	0.29	0.36	0.32	0.29
ρ*(0)	0.011	0.014	0.012	0.012	0.012	0.016

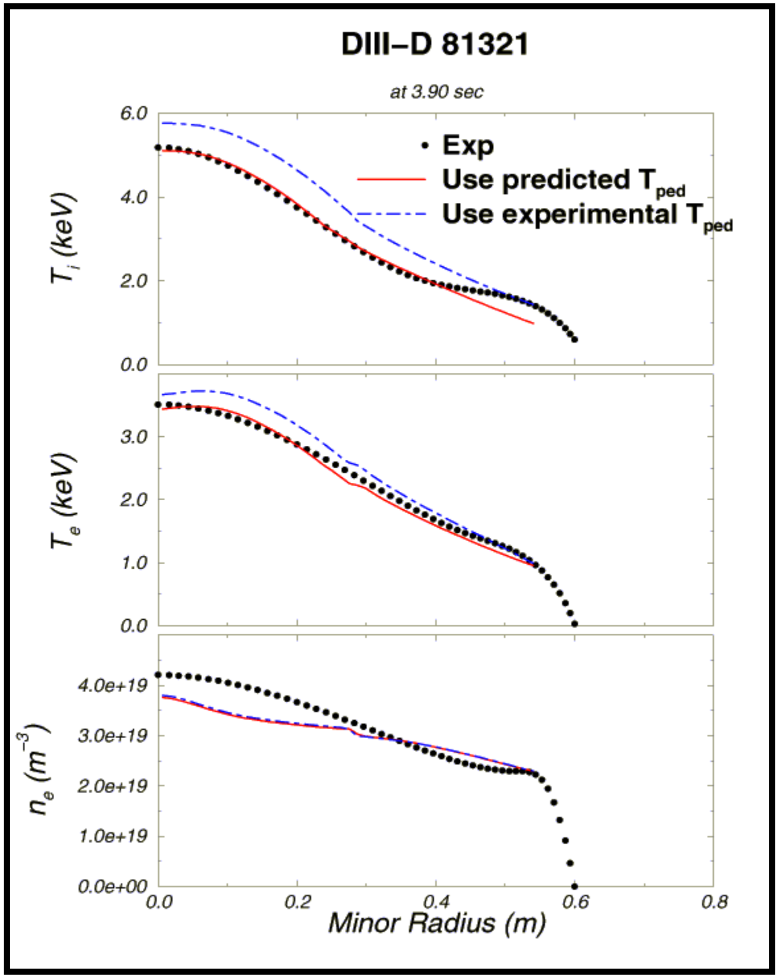
Simulations of Power Scan

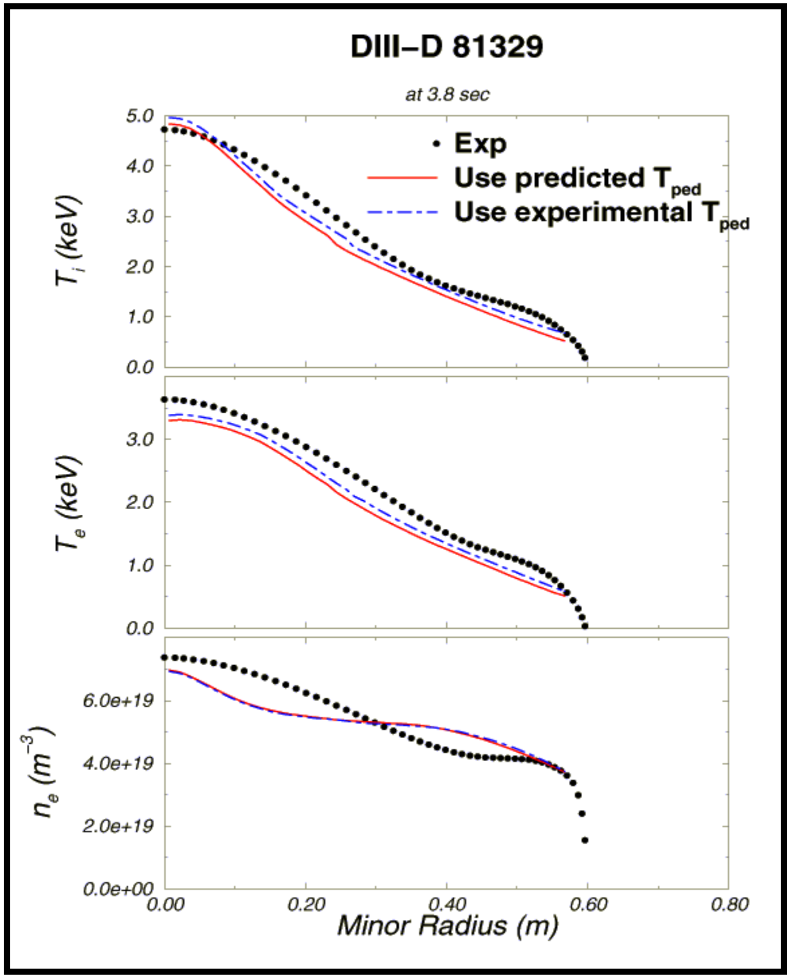




Model based on pedestal width scaling $\Delta \propto \rho s^2$

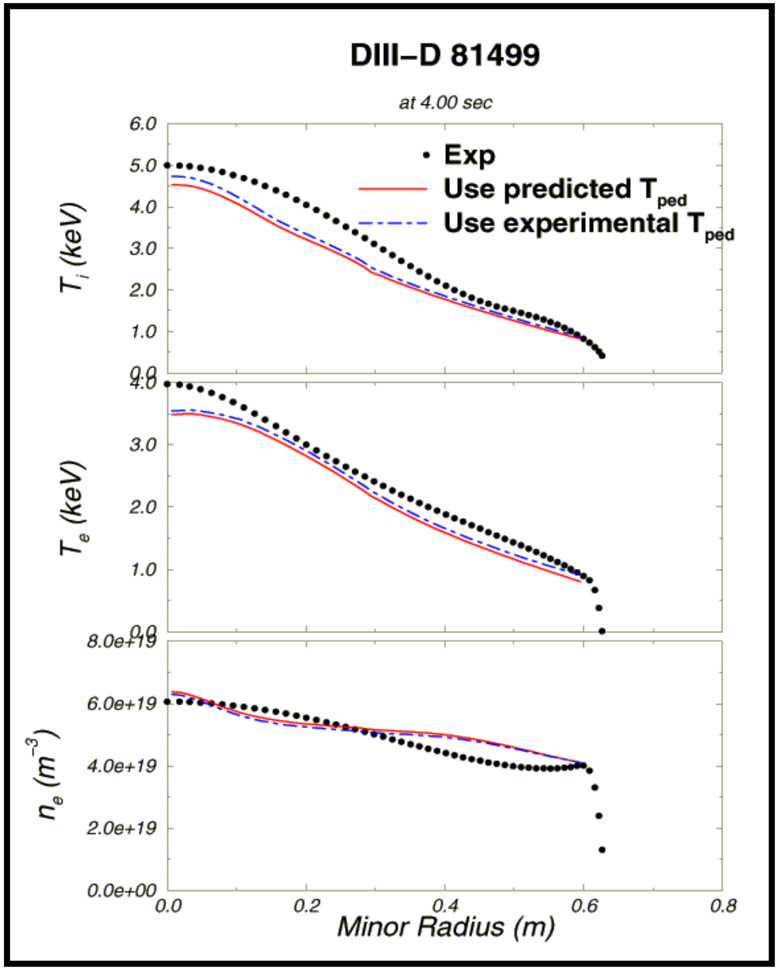
Simulations of Density Scan

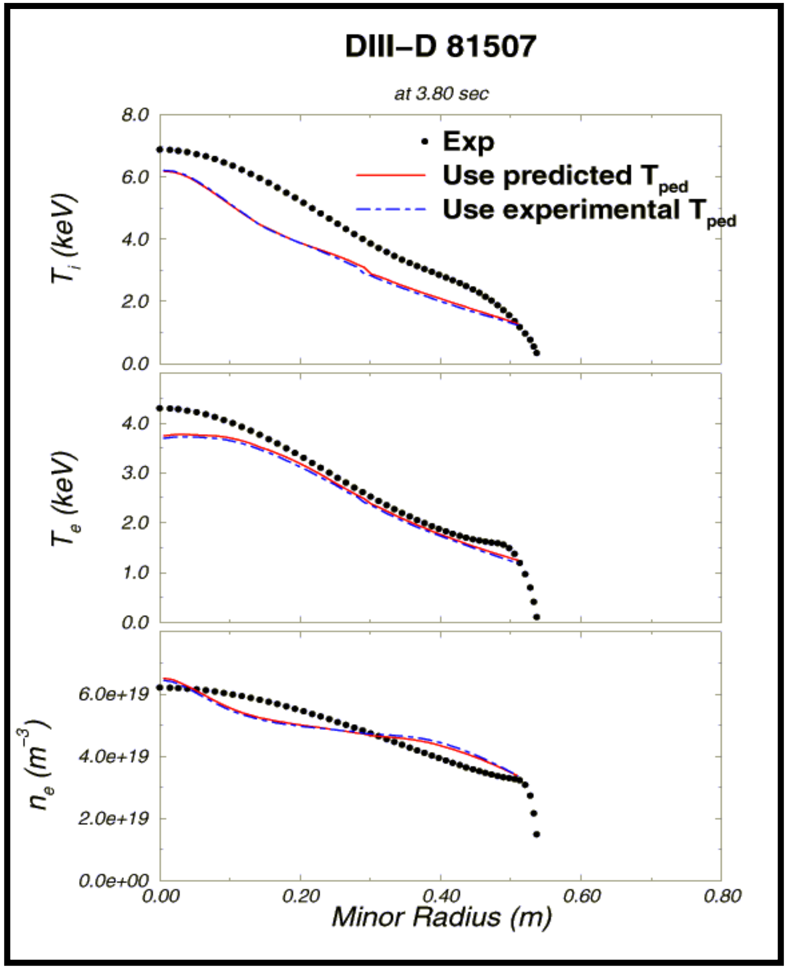




Model based on pedestal width scaling $\Delta \propto \rho\, s^2$

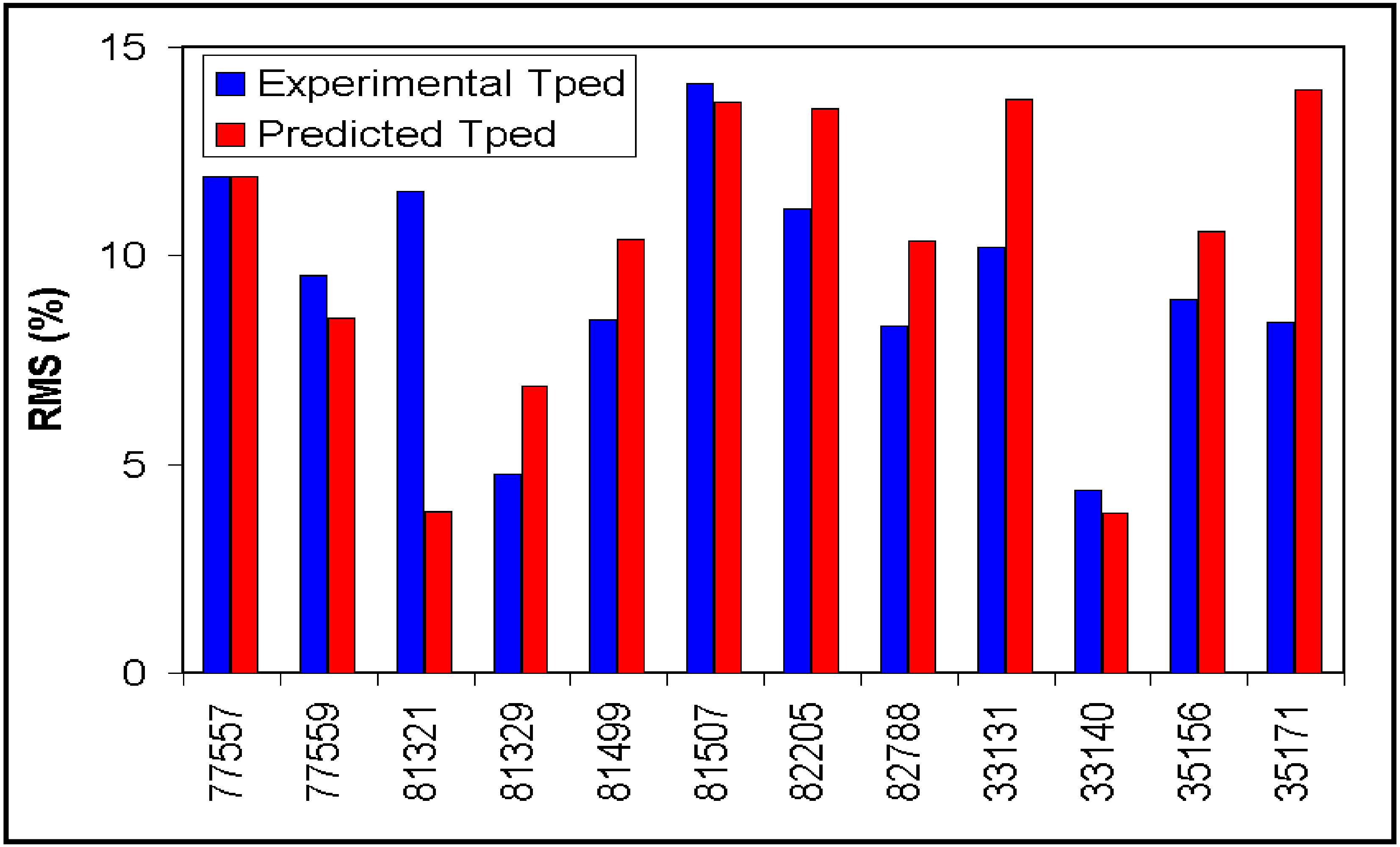
Simulations of Elongation Scan



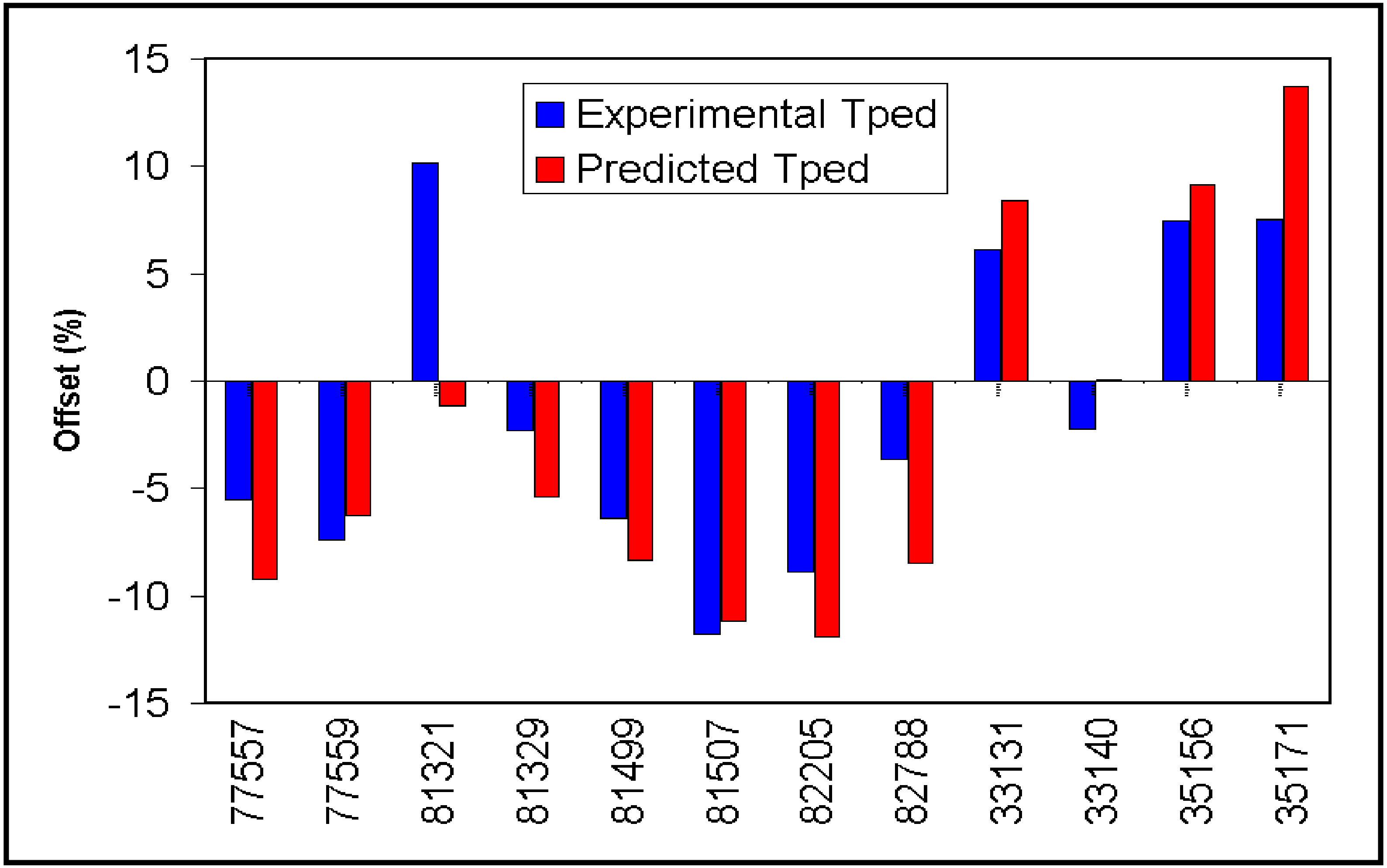


Model based on pedestal width scaling $\Delta \propto \rho\, s^2$

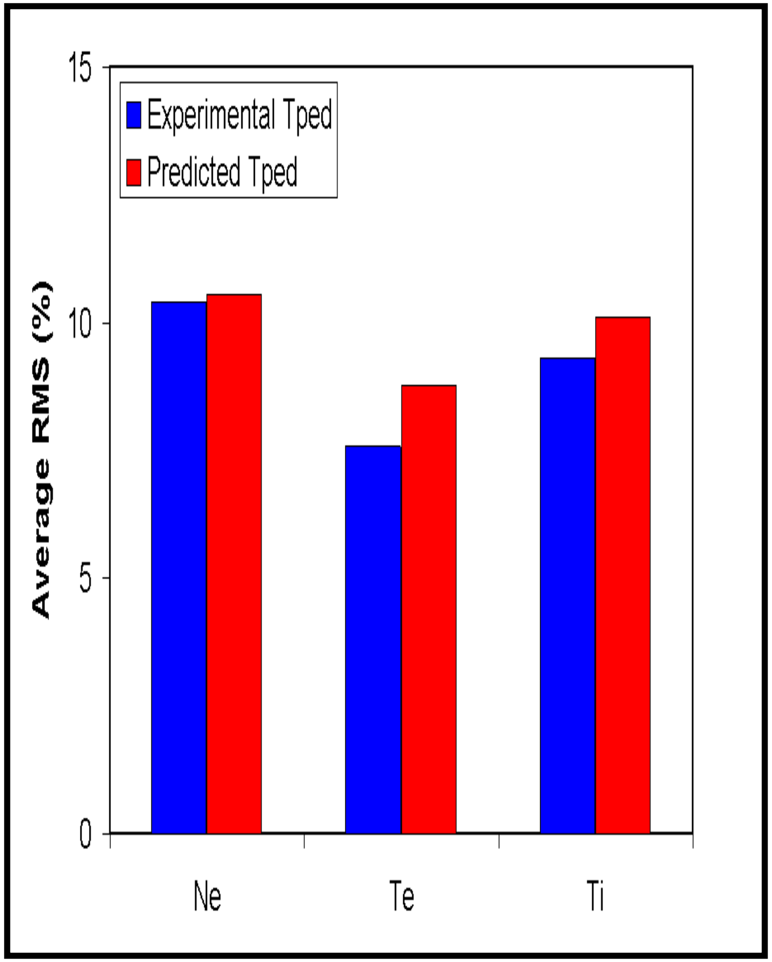
RMS Errors for T_i Profile

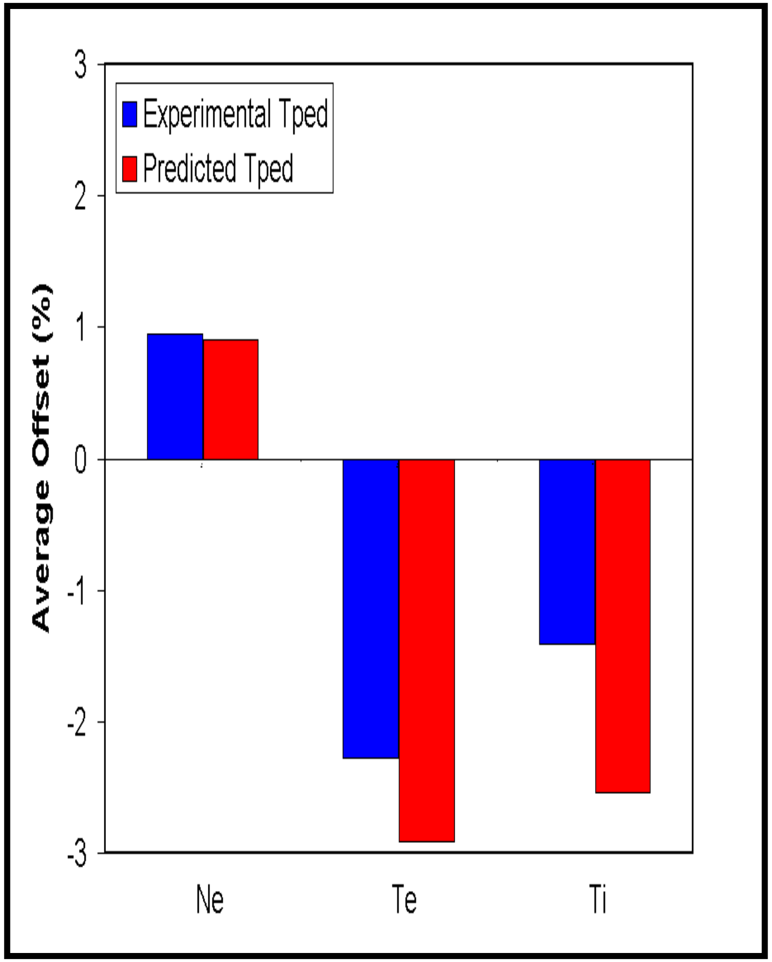


Offsets for T_i Profile

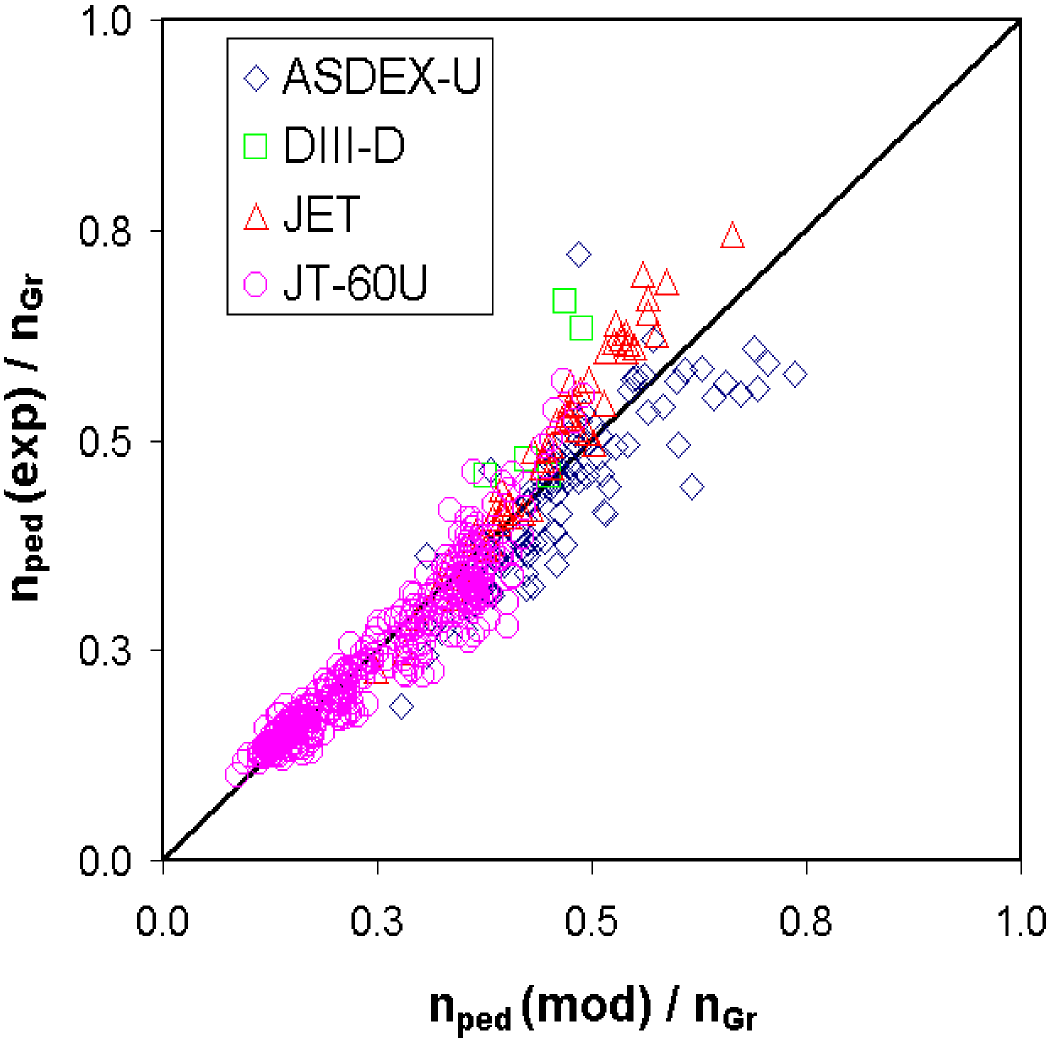


Average RMS Errors and Offsets





H-mode Pedestal Density Scaling



- **Empirical fit for density model**

$$n_{ped} = 0.71\bar{n}$$

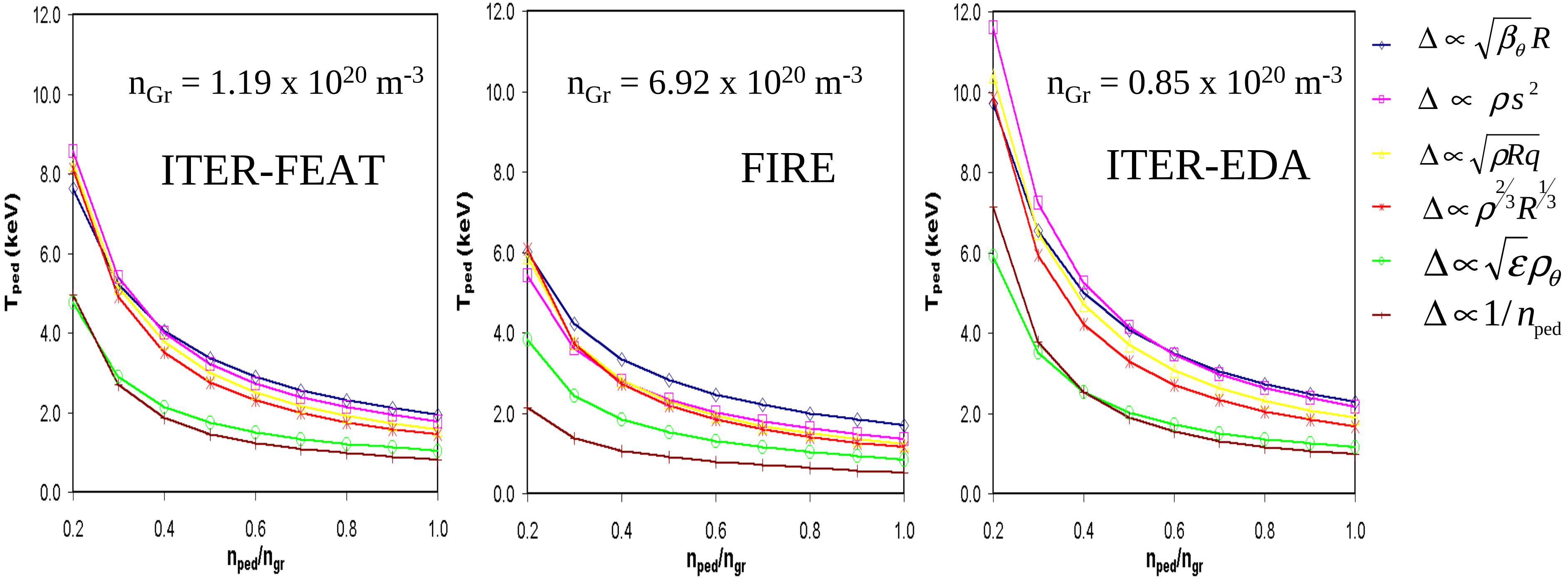
- **RMS = 12.1%**
- **Agreement breaks down at high density**

Integrated Modeling Simulations of ITER-FEAT and FIRE

- **The BALDUR code is used to simulate fusion reactor designs ITER-FEAT and FIRE**
  - **BALDUR predicts the time evolution of plasma profiles temperature, density, current, power, Z_{eff}, neutrals, …**
- **The objectives are to predict the performance of fusion reactor designs**
  - **Fusion power produced**
  - **Optimization of scenarios**
  - **Effect of varying density, Z_{eff}, auxiliary heating power**
  - **Effect of using different models**

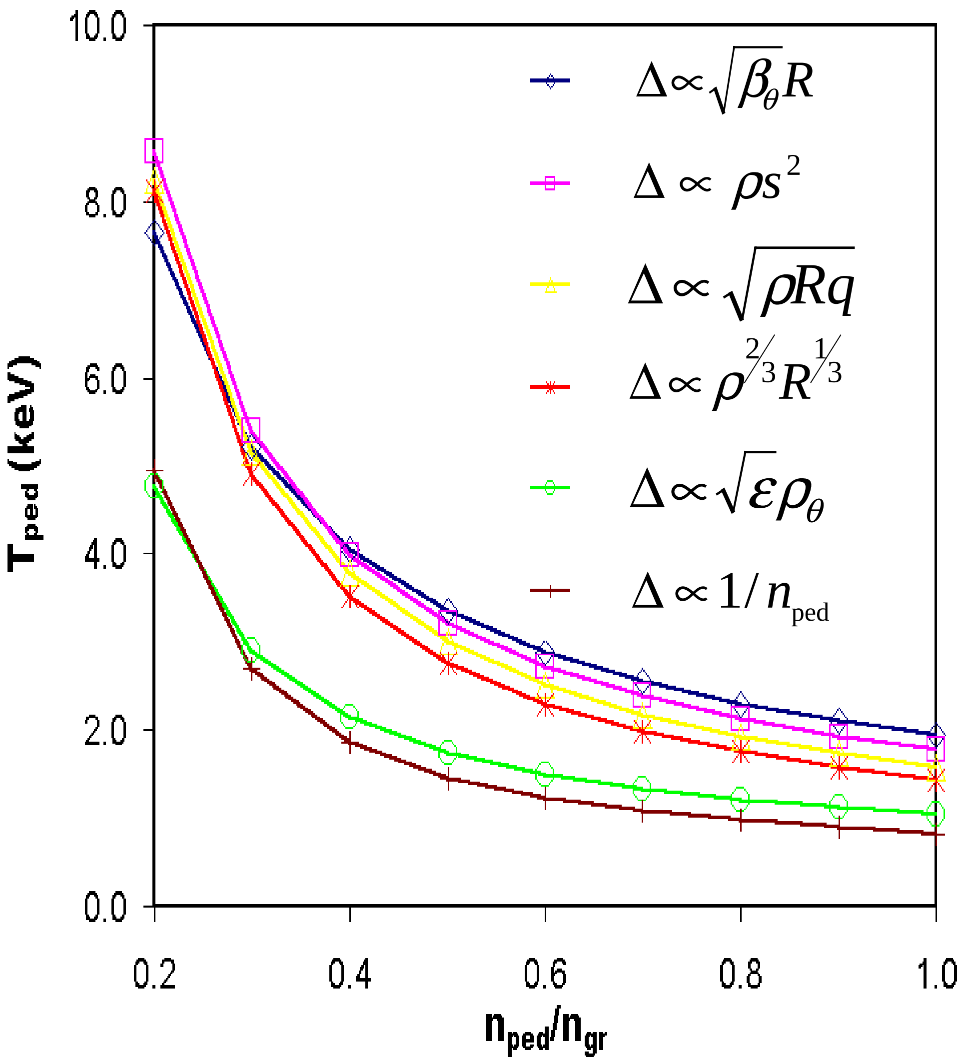
Applications of T_{ped} Models

- **Predict the edge temperature for future tokamak designs such as ITER-FEAT, FIRE and ITER-EDA**



(Note that Ignitor is designed to operate in L-mode)

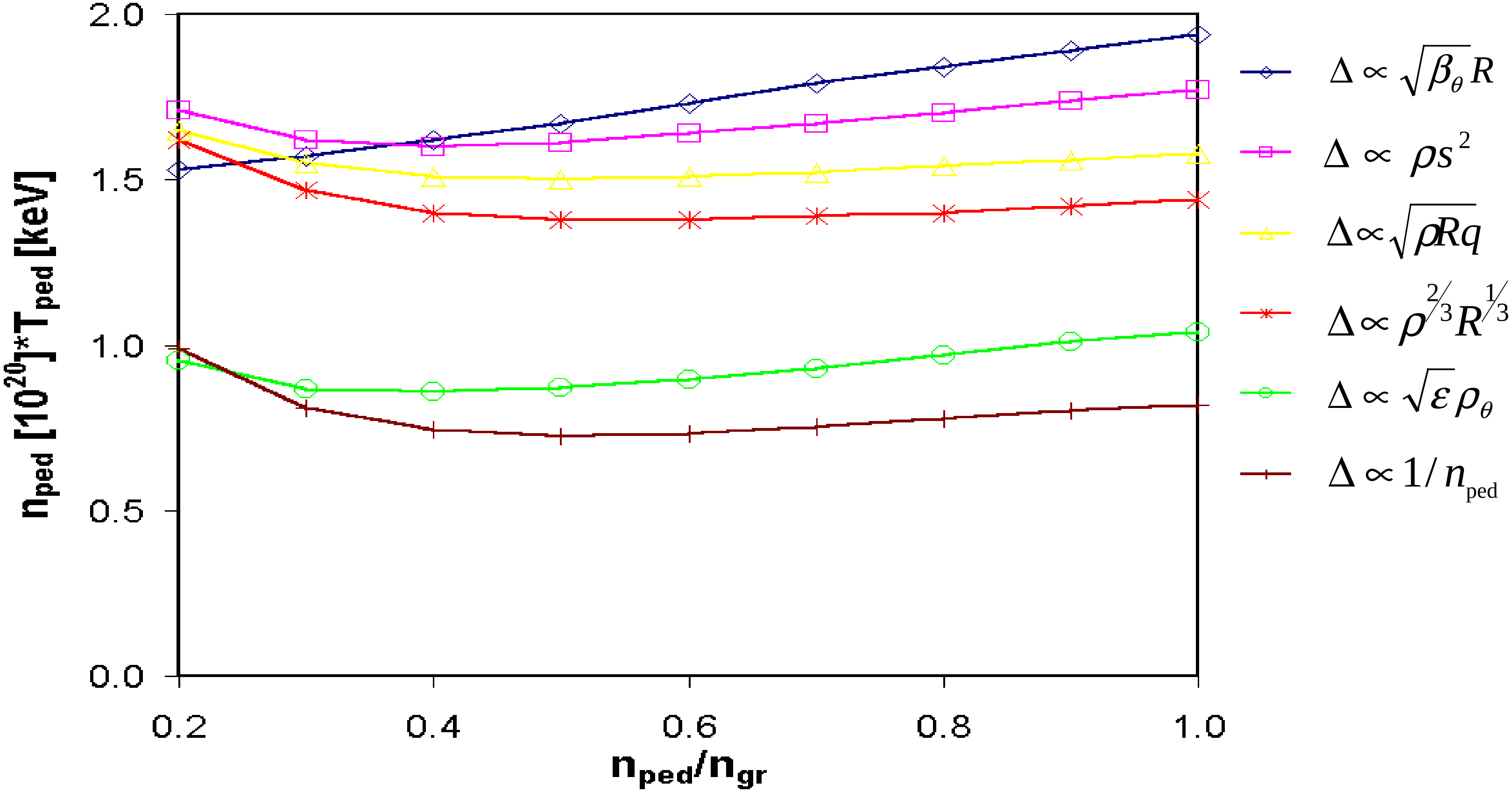
Pedestal Temperature Predicted for ITER-FEAT



Parameters for ITER-FEAT

R	6.2 m
a	2.0 m
I	15.0 MA
B	5.3 tesla
κ_{95}	1.7
δ_{95}	0.33
Z_{eff}	1.9
A_H	2.5 AMU
P_{aux}	40 MW

Pedestal Pressure Predicted for ITER-FEAT

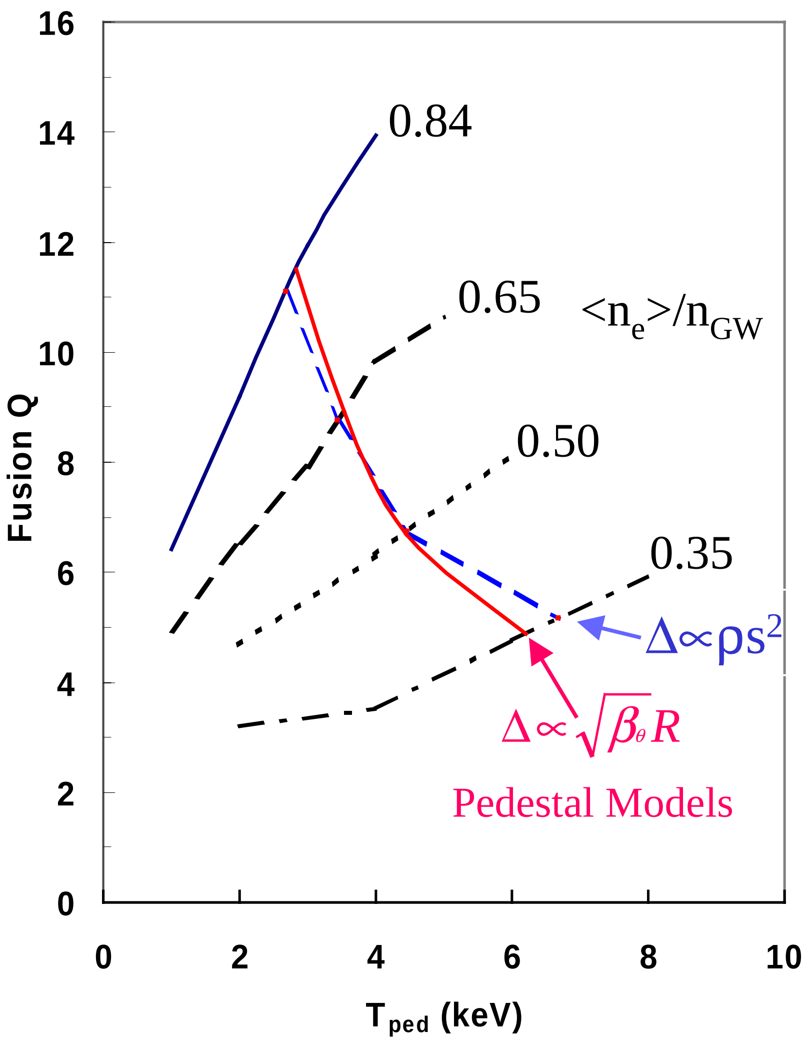


Pedestal pressure is almost independent of the pedestal density

Effect of the Pedestal Models in Integrated Predictive Simulations of ITER and FIRE

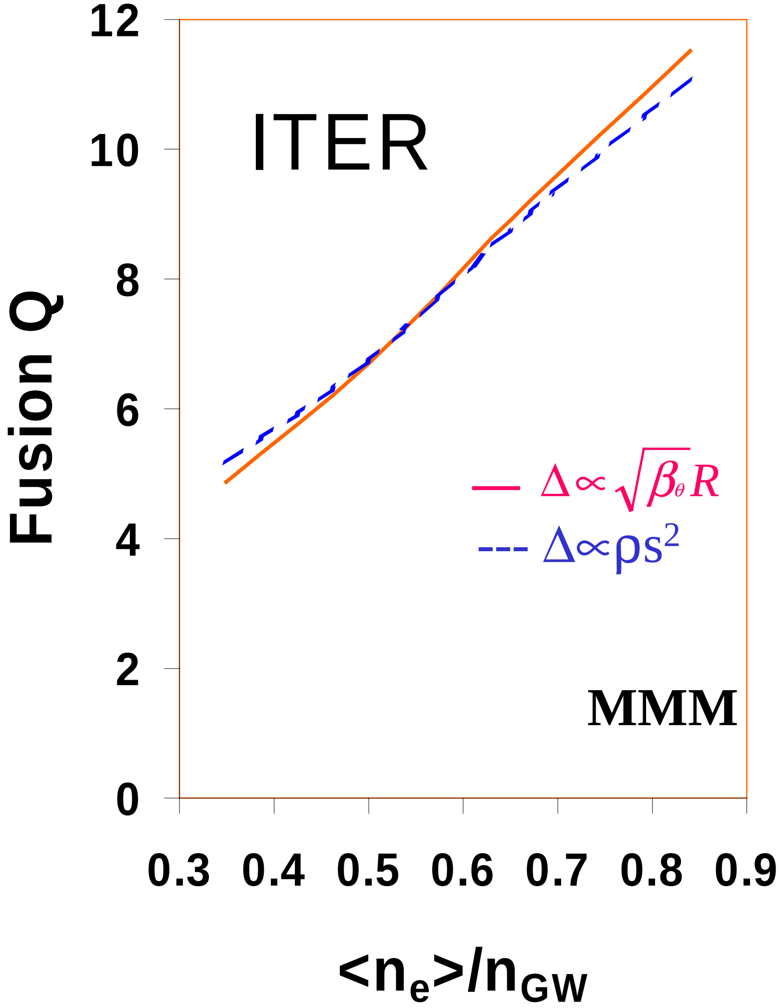
- **Effect of changing plasma density and heating power:**
  - **The pedestal density is proportional to the average plasma density**
  - **The pedestal temperature in type I ELMy H-mode plasmas is**
    - **independent of heating power, and**
    - **T_{ped} is nearly inversely proportional to n_{ped} (for all of the models)**
  - **The core temperature profile depends sensitively on the pedestal temperature because the core transport models are stiff**
  - **Fusion power production scales like n^2T^2 for $10 < T_i < 20$ keV**
- **Hence, increasing the plasma density causes the following:**
  - **Pedestal density increases proportional to average plasma density**
  - **Pedestal temperature decreases with increasing density**
  - **For perfectly stiff core transport model, n^2T^2 remains nearly constant**
  - **Fusion power from the region $10 < T_i < 20$ keV remains constant**

Fusion Q vs T_{ped} for ITER-FEAT



- **Fusion $Q \equiv 5\, P_\alpha / P_{aux}$**
- **ITER-FEAT with P_{aux} = 40 MW with 2% Be + 0.12% Ar + Helium**
- **These simulations use the Multi-Mode transport model and a choice of two pedestal models**
- **With density held fixed, the fusion *Q* rises rapidly with T_{ped}**
- **However, only plasma density can be controlled — pedestal models indicate that T_{ped} is inversely related to n_{ped}**
- **Note that fusion power $\propto n^2 T^2$ for $10 < T < 20$ keV**
- **Here, fusion power decreases at higher temperature and lower density**

Fusion Q vs $<n_e>/n_{GW}$ for ITER-FEAT

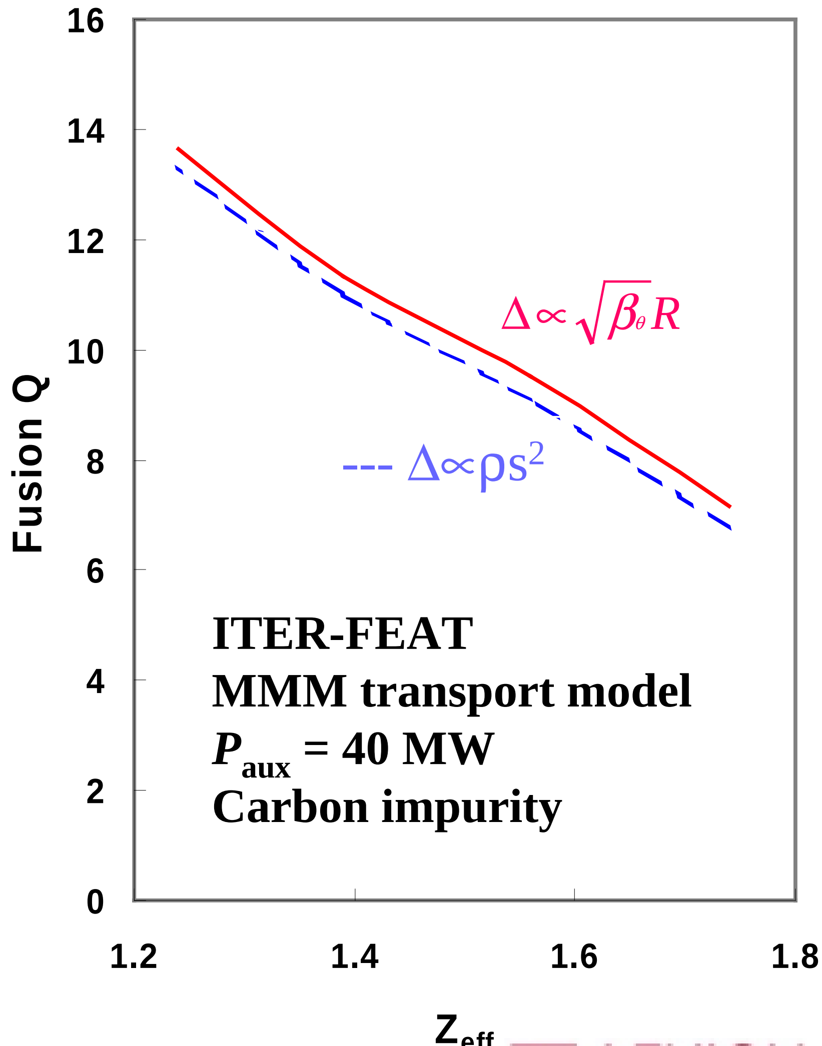


- **Multi-Mode model used in BALDUR simulations of ITER-FEAT density scan**
  - **Fusion $Q \equiv P_\alpha / P_{aux}$**
  - **$<n_e>/n_{GW} \equiv$ average plasma density normalized by the Greenwald density**

    $n_{GW} = I_p/(\pi a^2) = 1.1\times10^{20}$ m^{-3}
  - **P_{aux} = 40 MW**
  - **2% Be + 0.12% Ar + Helium yields $Z_{eff} \approx 1.5$**
- **Plasma density can be controlled in tokamaks, but not pedestal temperature**
  - **T_{ped} from all of the pedestal models inversely related to density**
  - **T_{i0} varies from 29 to 19 keV as density is increases from $<n_e>/n_{GW}$ = 0.35 to 0.85**

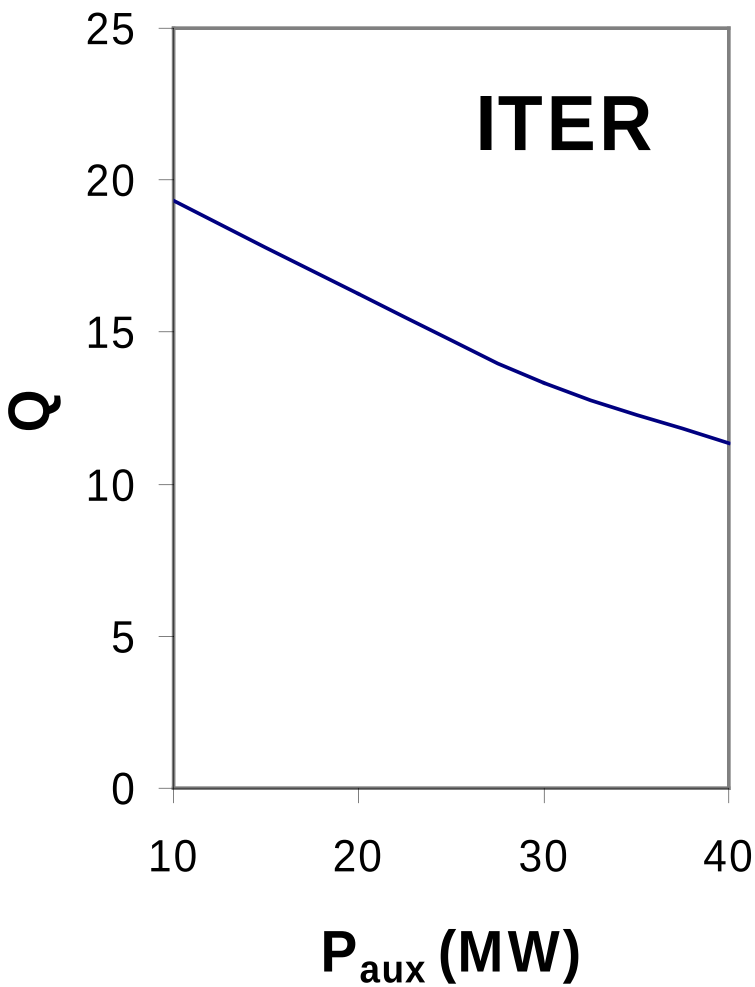
Effect of Z_{eff} on Fusion Q in ITER-FEAT

- **Increasing Z_{eff} decreases P_α and fusion Q**
  - **These simulations were carried out with Carbon impurity**
- **From previous studies of ITER-EDA**
  - **We know that the dilution caused by impurities has a strong effect on P_α**
  - **This effect is amplified in a marginal fusion burn**

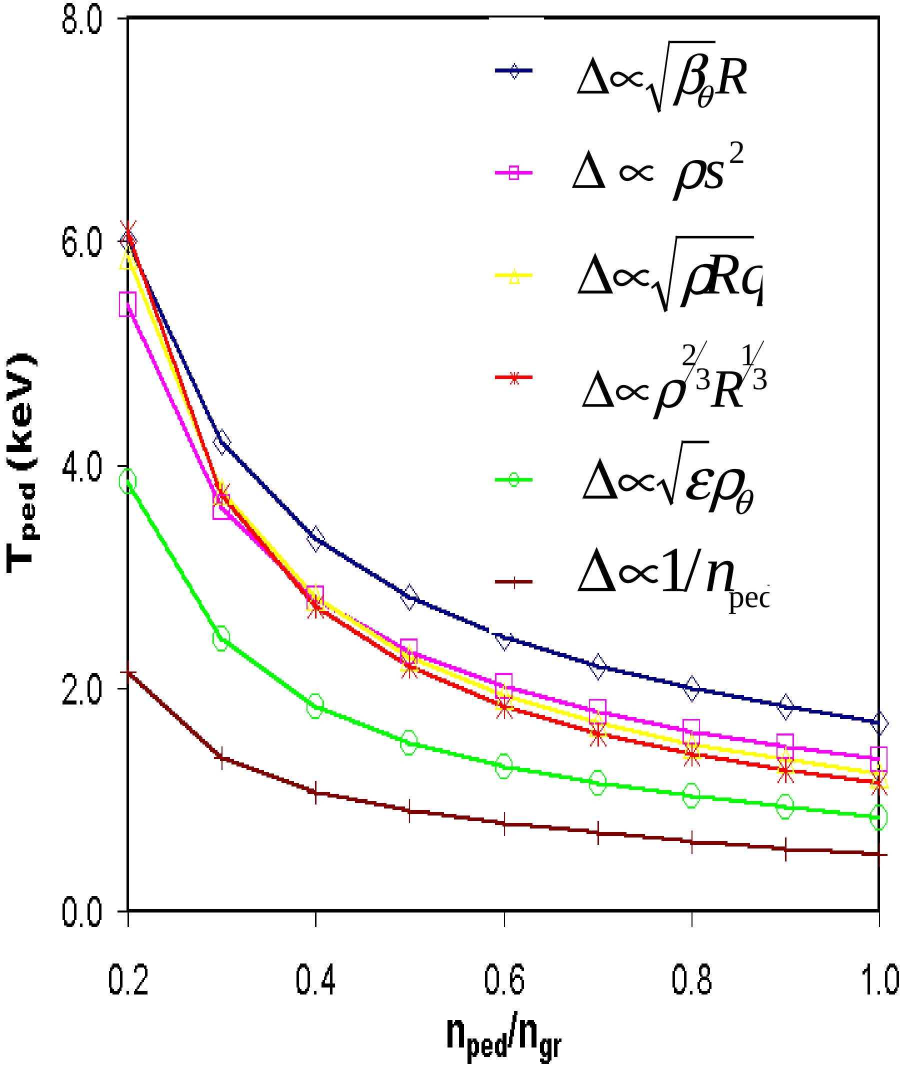


Effect of Auxiliary Heating Power on Fusion Q in ITER-FEAT

- **Largest fusion Q obtained with lowest auxiliary heating power**
  - **Plasma temperature profile and, hence, alpha heating power is only weakly dependent on heating power because of stiffness of transport model**
- **Cannot decrease total heating power below H-mode threshold (about 49 MW in ITER-FEAT)**
- **Here, $\langle n_e \rangle / n_{GW} = 0.84$**
  $n_{GW} = 1.1 \times 10^{20}$
  2% Be + 0.12% Ar + He

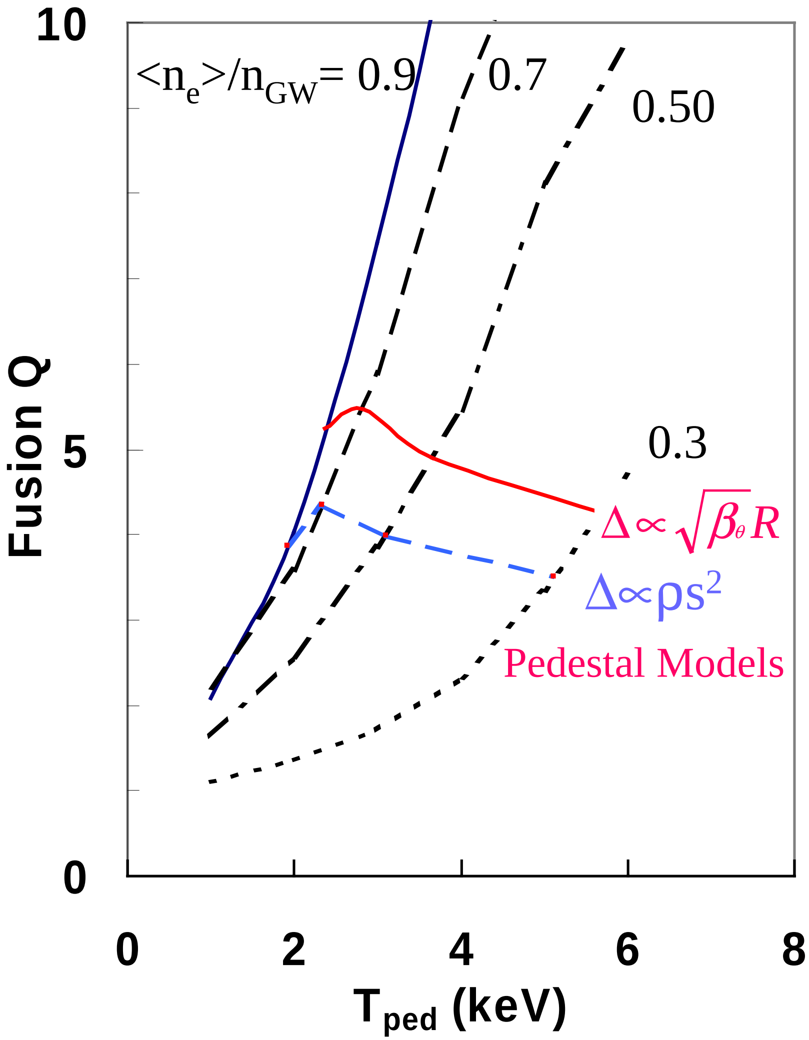


Pedestal Temperature Predicted for FIRE



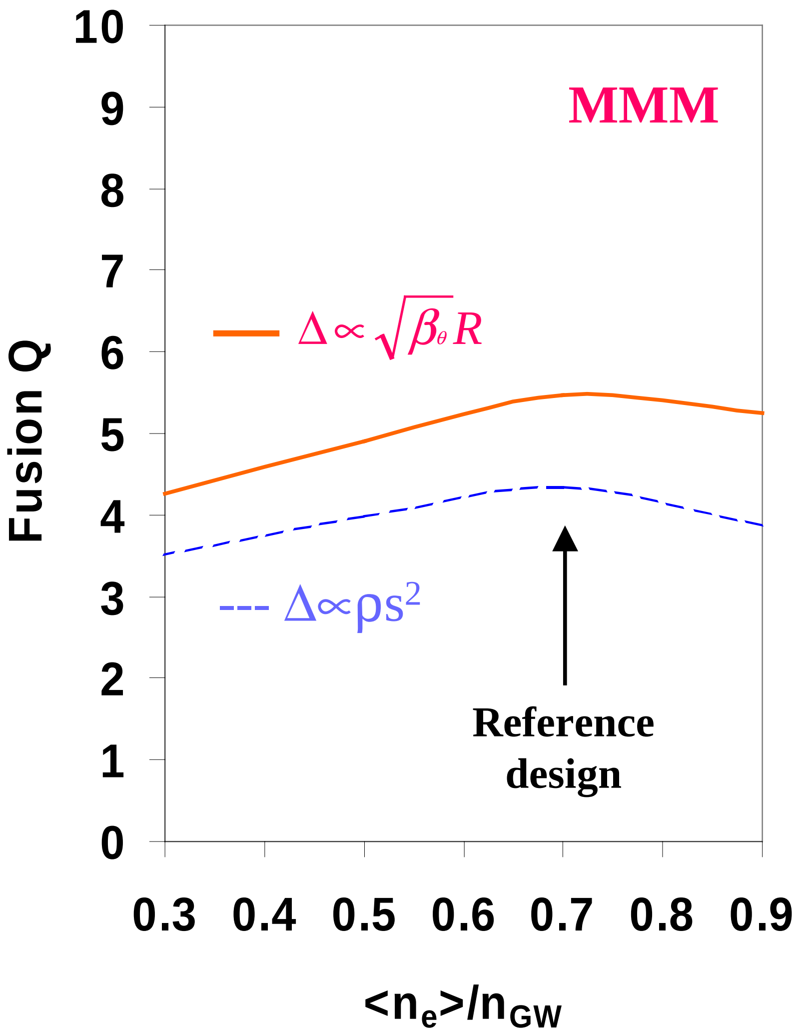
Parameters for FIRE	
R	2.14 m
a	0.595 m
I	7.7 MA
B	10 tesla
κ_{95}	1.77
δ_{95}	0.4
Z_{eff}	1.6
A_H	2.5 AMU
P_{aux}	20 MW

Fusion Q vs T_{ped} for FIRE



- **Fusion Q = 5 P_α / P_{aux}**
- **FIRE with R=2.14 m, a=0.595 m, B=10 tesla, I_p=7.7 MA, P_{aux} = 30 MW and Z_{eff} = 1.4**
- **These simulations use the Multi-Mode transport model and two pedestal models**
- **With density held fixed, the fusion Q rises with T_{ped}**
- **When using the pedestal models, T_{ped} is inversely related to n_{ped}**

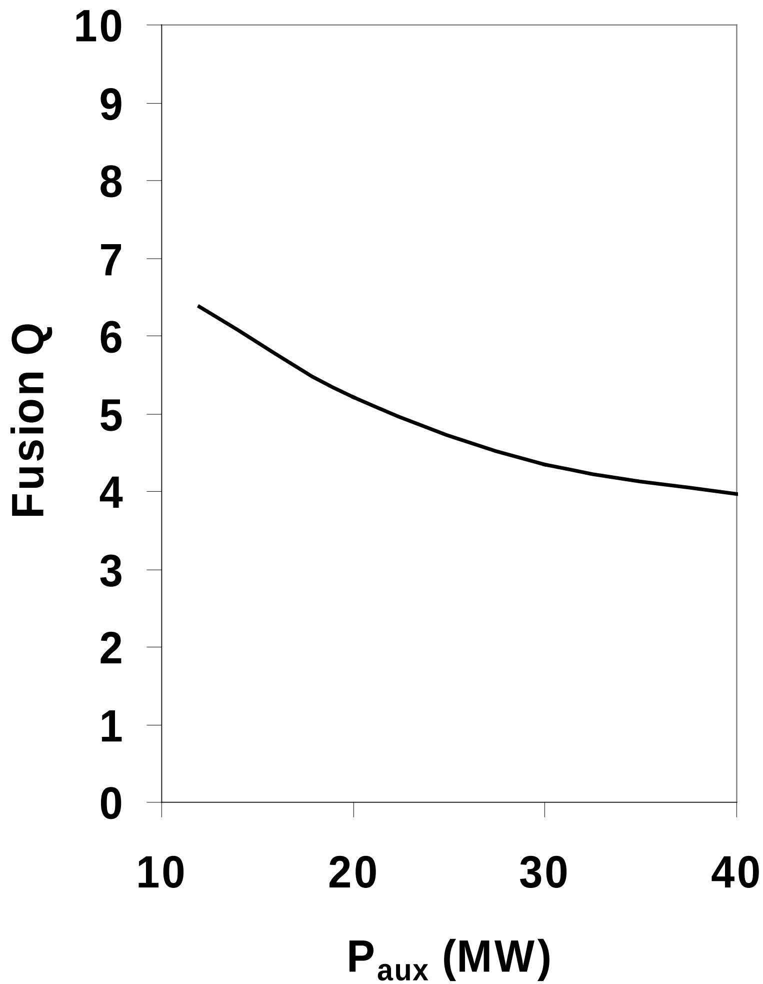
Fusion Q vs $\langle n_e \rangle$ for FIRE



- **BALDUR simulations of FIRE density scan using Multi-Mode transport model**
  - **Fusion $Q \equiv P_\alpha / P_{aux}$**
  - **$\langle n_e \rangle / n_{GW} \equiv$ average plasma density normalized by the Greenwald density**
    $n_{GW} = I_p / (\pi a^2) = 6.92 \times 10^{20}$
  - **P_{aux} = 30 MW, Z_{eff} = 1.4**
- **Plasma density can be controlled in tokamaks**
  - **T_{ped} from models inversely related to density**

Effect of Auxiliary Heating Power on Fusion Q in FIRE

- **Largest fusion Q obtained at lowest auxiliary heating power**
  - **Plasma temperature profile and, hence, alpha heating power is only weakly dependent on heating power because of stiffness of transport model**
- **Cannot decrease total heating power below H-mode threshold (about 26 MW)**
- **Here, $\langle n_e \rangle / n_{GW} = 0.7$**
  $n_{GW} = 6.92 \times 10^{20}$
  3% Be + Helium



Conclusions

- **H-mode pedestal temperature model can now be used as the boundary condition for integrated predictive modeling**
  - **Average RMS deviation is approximately 10%, which is nearly the same as when pedestal height is taken from experimental data**
  - **Improvement could be made by using separate models for the electron and ion pedestal temperatures**
  - **An automated procedure that predicts the onset of H-mode as well as models for $T_{e,ped}$, $T_{i,ped}$, and $n_{e,ped}$ will be tested this summer**
- **H-mode pedestal models used in BALDUR simulations of ITER-FEAT and FIRE fusion reactor designs**
  - **Predictions are made using Multi-Mode model for conventional H-mode scenarios (no Internal Transport Barriers or pellet injection)**
  - **Fusion Q = 11.4 for ITER with P_{aux} = 40 MW**
  - **Fusion Q = 5.5 for FIRE with P_{aux} = 20 MW**
  - **Fusion Q increases with decreasing P_{aux} and decreasing Z_{eff}**