ITPA-SSO
JAEA, Naka, Japan
2006/04/12

ITER advanced scenario simulation using TASK

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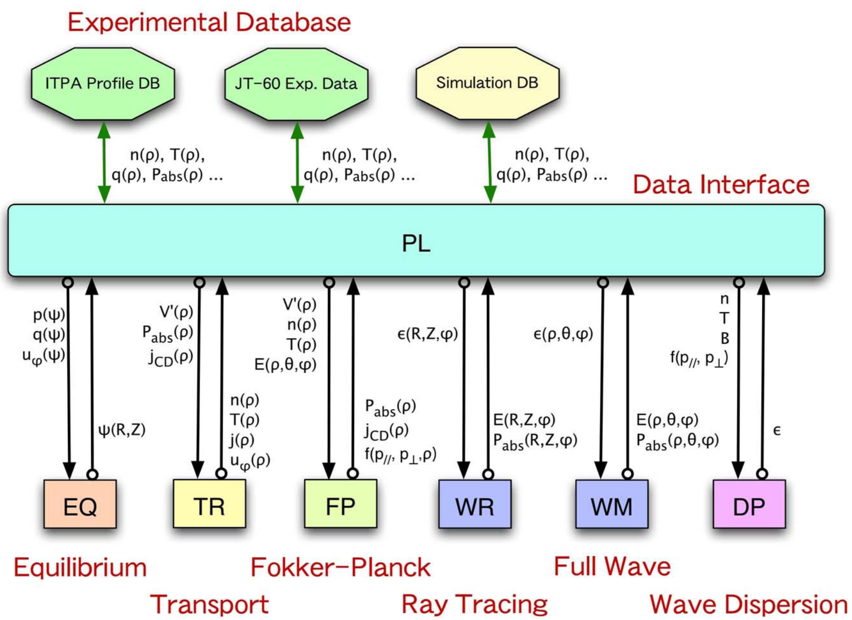
Outline

- TASK Code and CDBM05 transport model
- Comparison of transport models
- ITER transport simulation
- Dependence on initial current profile
- Summary

Structures of TASK

EQ	**2D Equilibrium**	Fixed boundary, Toroidal rotation
TR	**1D Transport**	Diffusive Transport, Transport models
WR	**3D Geometrical Optics**	EC, LH: Ray tracing, Beam tracing
WM	**3D Full Wave**	IC, AW: Antenna excitation, Eigen mode
FP	**3D Fokker-Planck**	Relativistic, Bounce-averaged
DP	**Wave Dispersion**	Local dielectric tensor, Arbitrary $f(\boldsymbol{v})$
PL	**Data Interface**	Data conversion, Profile database



CDBM Transport Model: CDBM05

- **Thermal Diffusivity** (Marginal: $\gamma = 0$)

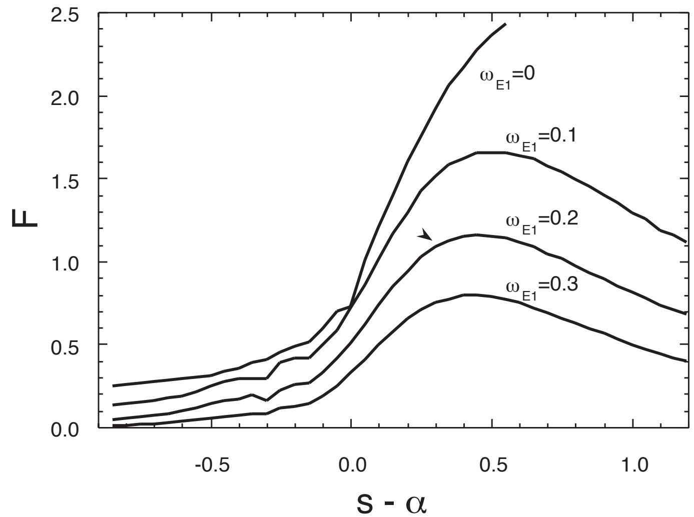
$$\chi_{\rm TB} = F(s, \alpha, \kappa, \omega_{\rm E1})\, \alpha^{3/2} \frac{c^2}{\omega_{\rm pe}^2} \frac{v_{\rm A}}{qR}$$

Magnetic shear	$s \equiv \dfrac{r}{q} \dfrac{{\rm d}q}{{\rm d}r}$
Pressure gradient	$\alpha \equiv -q^2 R \dfrac{{\rm d}\beta}{{\rm d}r}$
Elongation	$\kappa \equiv b/a$
$E \times B$ **rotation shear**	$\omega_{\rm E1} \equiv \dfrac{r^2}{s v_{\rm A}} \dfrac{\rm d}{{\rm d}r} \dfrac{E}{rB}$

- **Weak and negative magnetic shear, Shafranov shift, elongation, and $E \times B$ rotation shear**

reduce thermal diffusivity.

$s - \alpha$ dependence of $F(s, \alpha, \kappa, \omega_{\rm E1})$



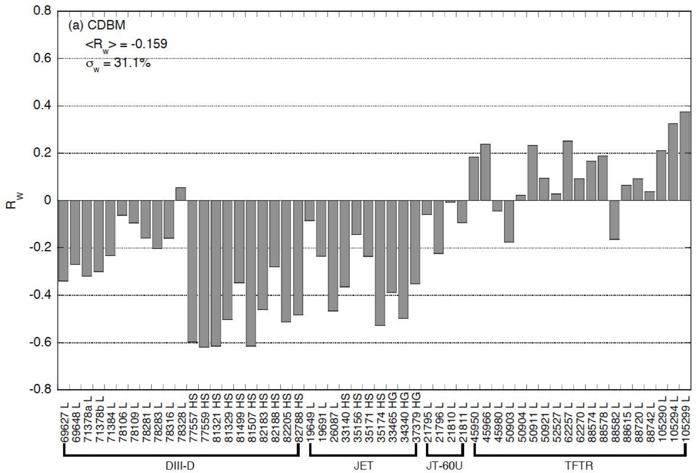
$$F(s, \alpha, \kappa, \omega_{\rm E1}) = \left(\frac{2\kappa^{1/2}}{1+\kappa^2} \right)^{3/2}$$

$$\times \begin{cases} \dfrac{1}{1+G_1 \omega_{\rm E1}^2} \dfrac{1}{\sqrt{2(1-2s')(1-2s'+3s'^2)}} & \text{for} \quad s' = s - \alpha < 0 \\[2ex] \dfrac{1}{1+G_1 \omega_{\rm E1}^2} \dfrac{1 + 9\sqrt{2} s'^{5/2}}{\sqrt{2}(1-2s'+3s'^2+2s'^3)} & \text{for} \quad s' = s - \alpha > 0 \end{cases}$$

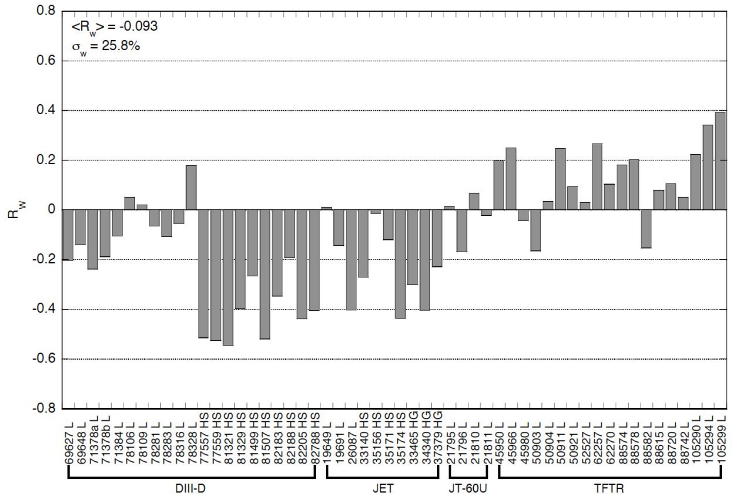
Comparison of Transport Models: ITPA Profile DB

Deviation of Stored Energy

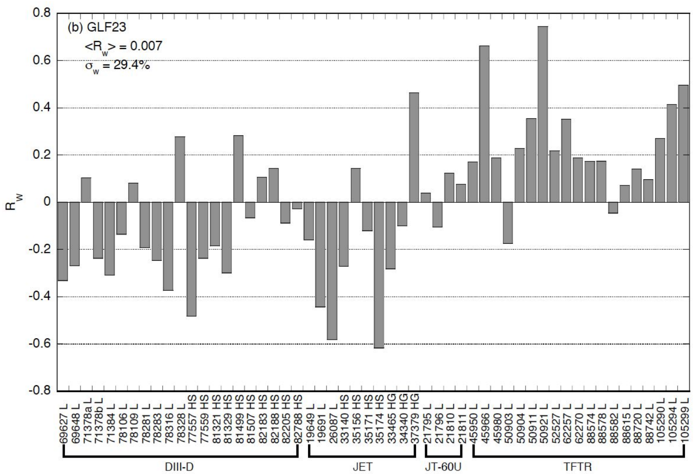
CDBM



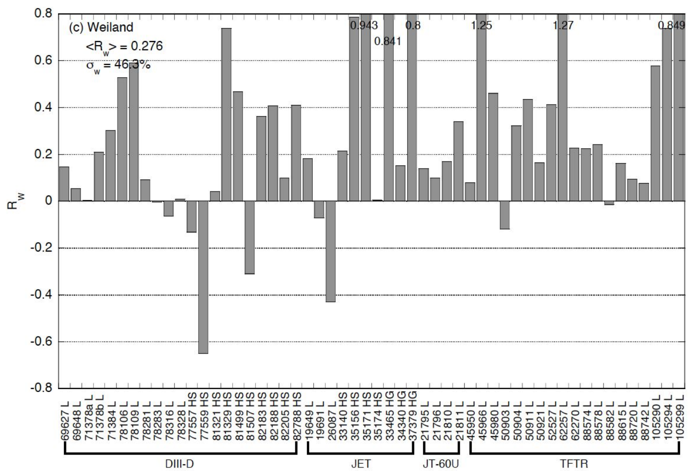
CDBM05



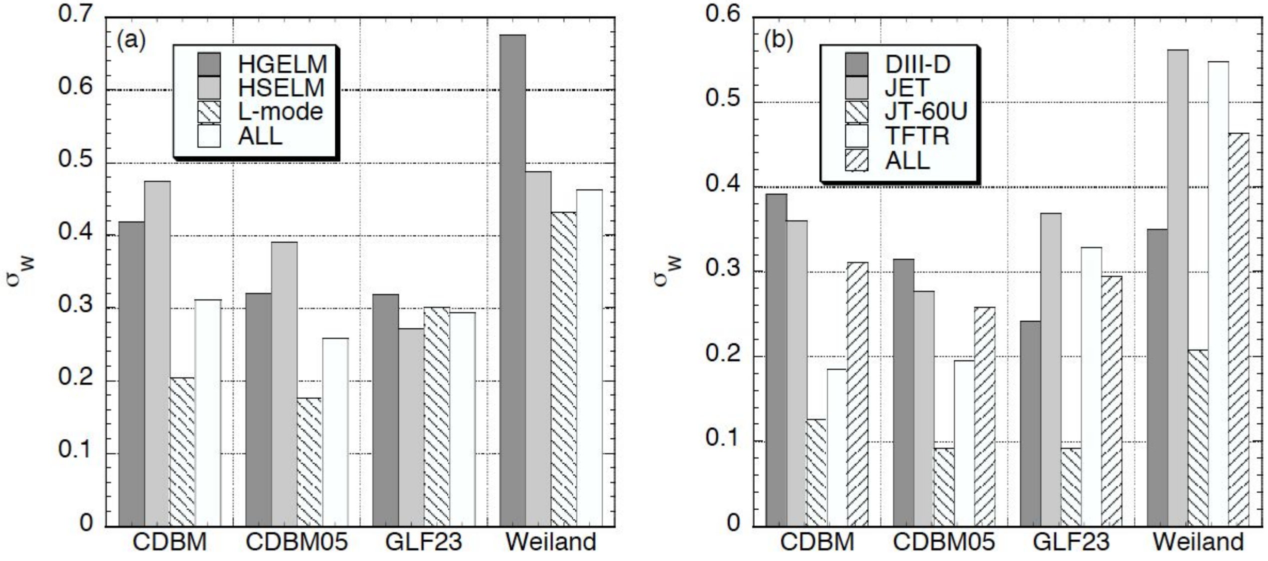
GLF23



Weiland



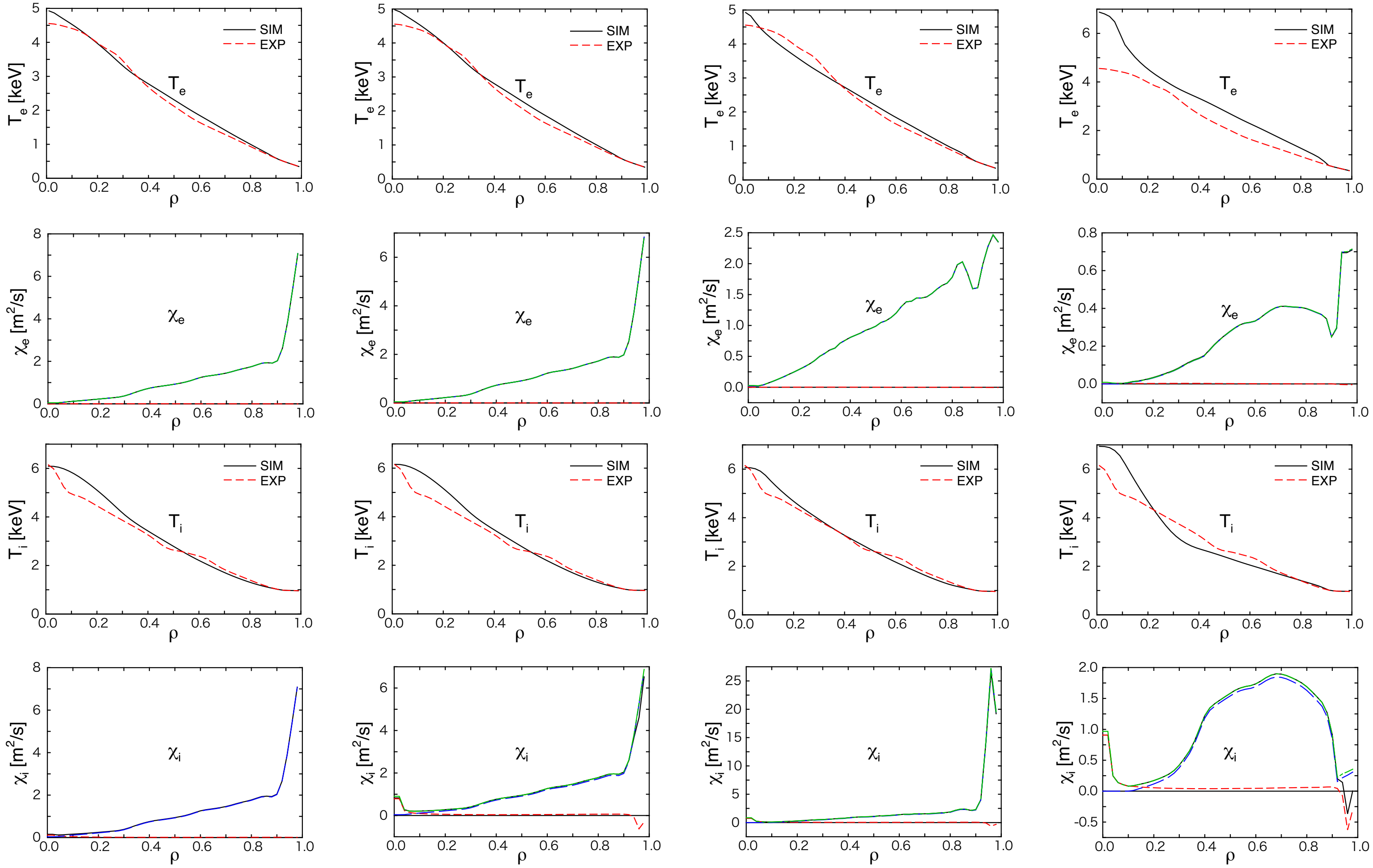
Dependence on Operation Mode and Devices



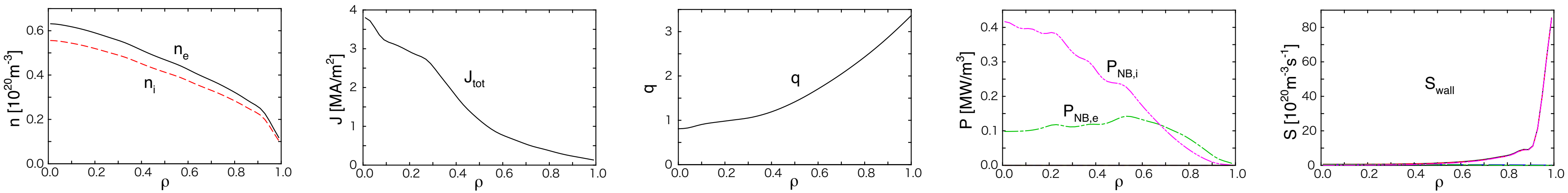
- Both CDBM05 and GLF23 reproduce the ITPA profile database pretty well.
- CDBM05 describes L-mode discharges better than GLF23.
- Both CDBM05 and GLF23 reproduces T_i much better than T_e, when the temperature of the other species is fixed to the experimental value.

TFTR #88615 (L-mode, NBI heating)

CDBM CDBM05 GLF23 Weiland

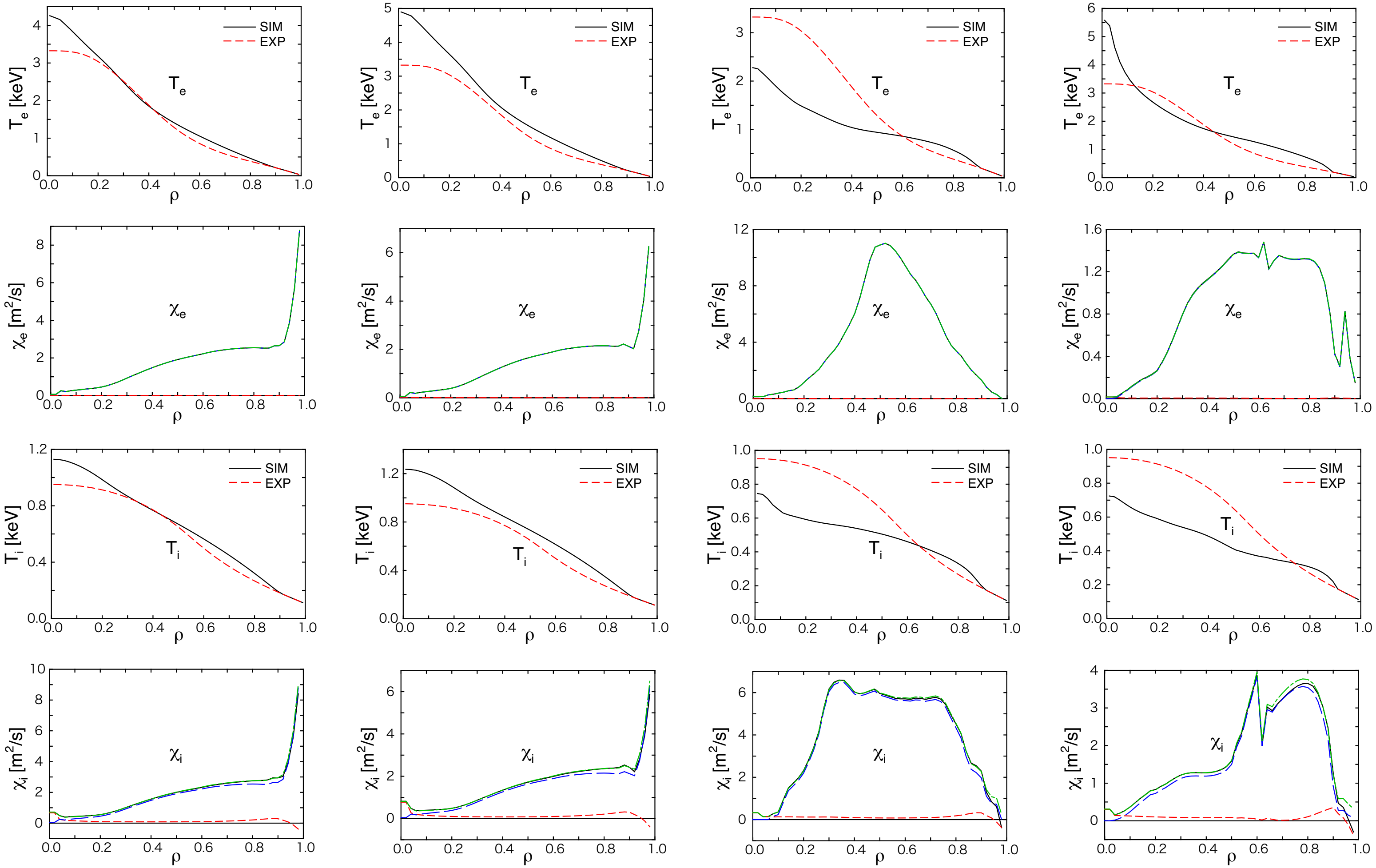


Common Profiles

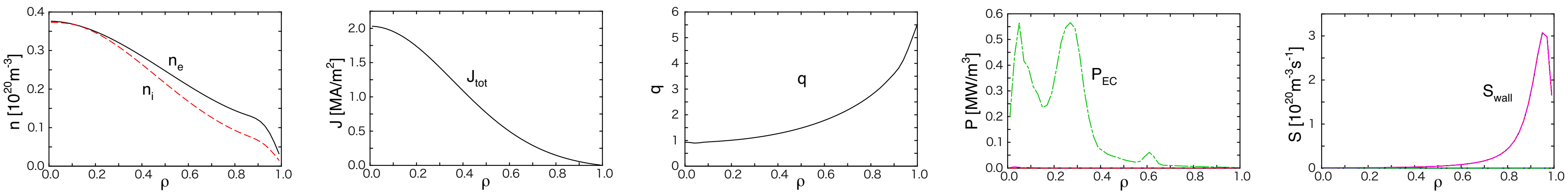


DIII-D #78316 (L-mode, ECH and ICH heatings)

CDBM | CDBM05 | GLF23 | Weiland



Common Profiles



ITER Simulations

- **Using the CDBM and CDBM05 models**
  - Both models could reproduce $T_{\mathrm{e,i}}$ profiles for L- and H-mode shots reasonably.
  - The prediction of high performance plasmas is anticipated with the CDBM05 model rather than the CDBM model.
- **Using simple heating and current drive models**
  - Power deposition profile is assumed.
  - Approximate analytic formula is assumed as a current drive efficiency.
- **Searching parameters predicting ITER operation scenarios**
  - Strong self-regulation of the plasma and nonlinearity of the transport model make it more difficult to predict the confinement performance.
- **In this simulation**
  - Density profiles are fixed as H-mode like profiles.
  - **TASK/TR is coupled with the 2-D equilibrium code, TASK/EQ.**
  - It solves the time evolution of the thermal transport and the magnetic diffusion.
  - Radiation losses caused by carbon and bremsstrahlung are taken into account ($Z_{\mathrm{eff}} \approx 1.5$).

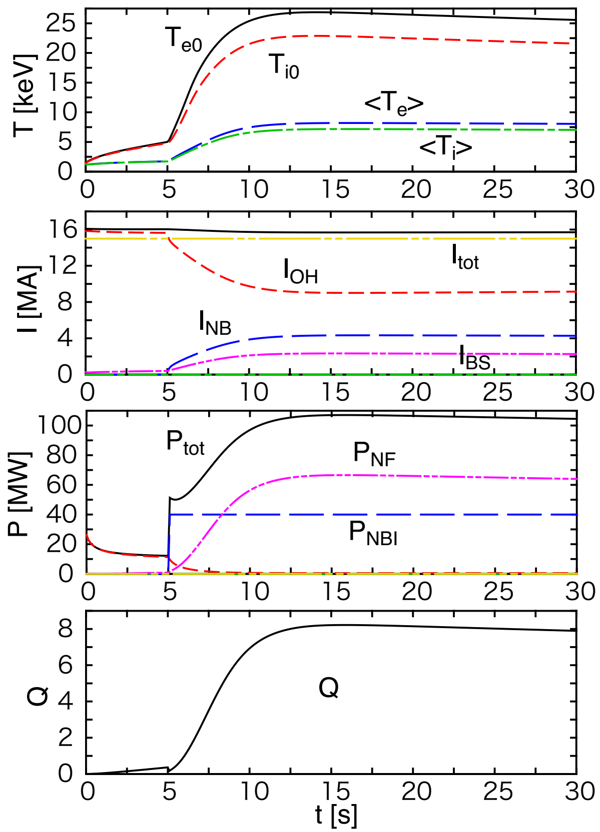
High Q Operational Scenario

- Large plasma current: $I_p = 15$ MA, On-axis heating: $P_{NB} = 40$ MW
- Positive shear profile, Relatively large f_{OH}

CDBM

$\beta_N = 1.49$

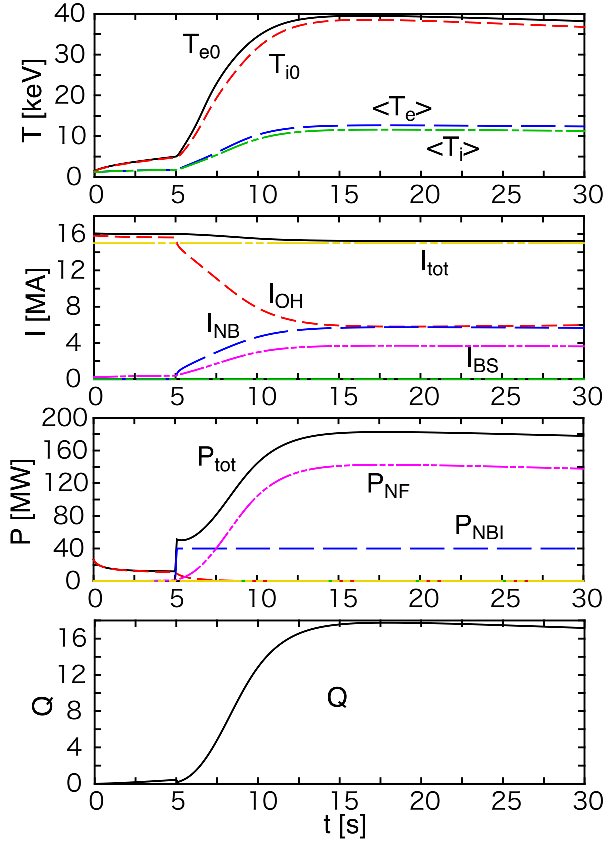
$\tau_E = 3.0$ s

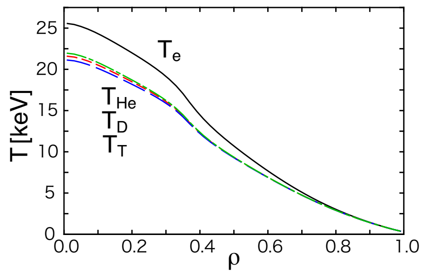


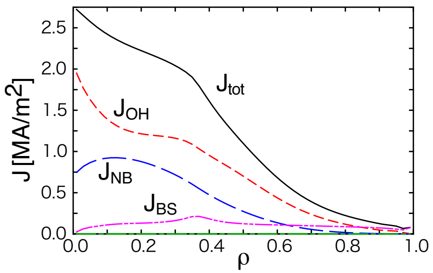
CDBM05

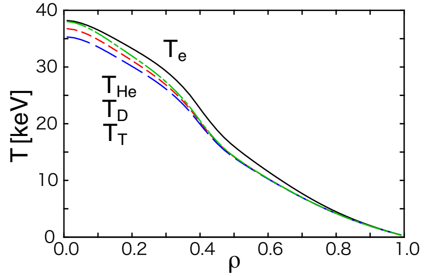
$\beta_N = 2.63$

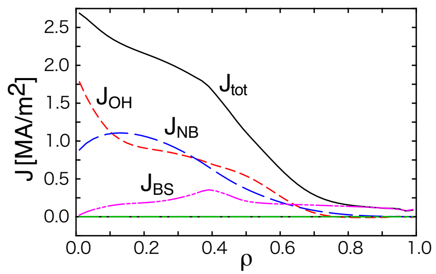
$\tau_E = 3.1$ s











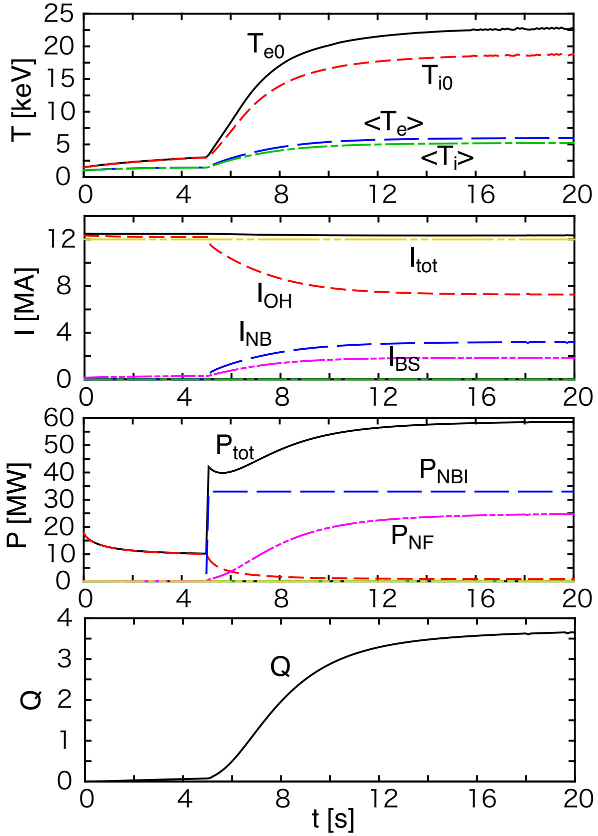
Hybrid Operational Scenario

- Moderate plasma current: $I_\mathrm{p} = 12$ MA, On-axis heating: $P_\mathrm{NB} = 33$ MW
- Flat q profile with small ITB inside $\rho = 0.4$

CDBM

$\beta_\mathrm{N} = 1.17$

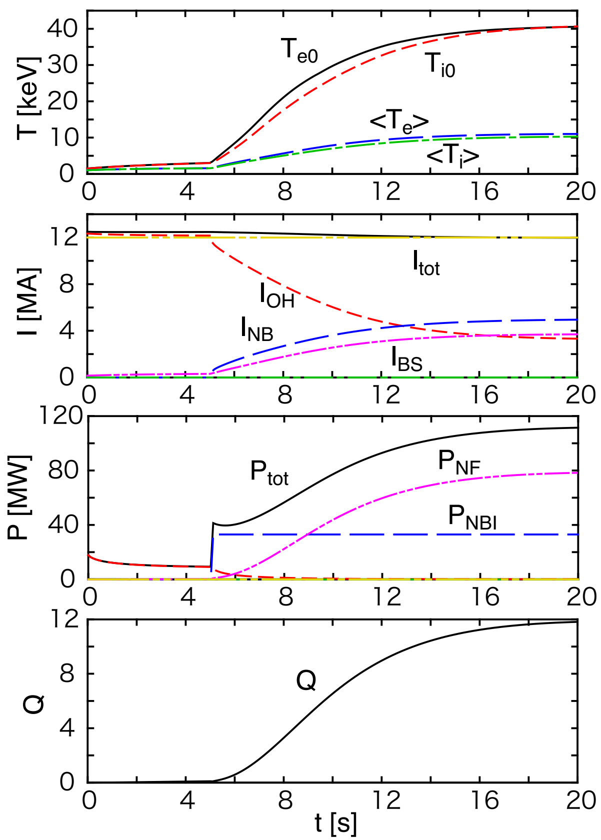
$\tau_\mathrm{E} = 3.1$ s

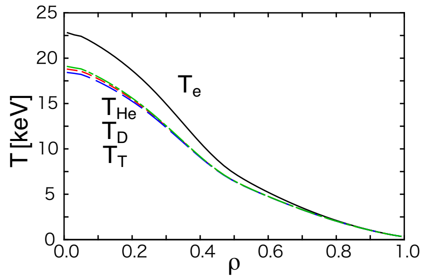


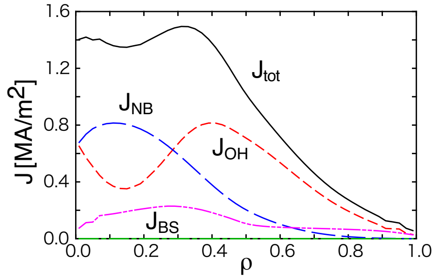
CDBM05

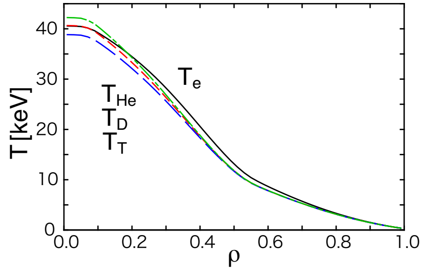
$\beta_\mathrm{N} = 2.58$

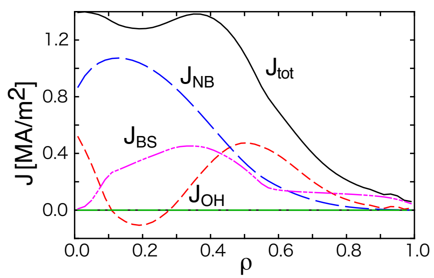
$\tau_\mathrm{E} = 3.6$ s











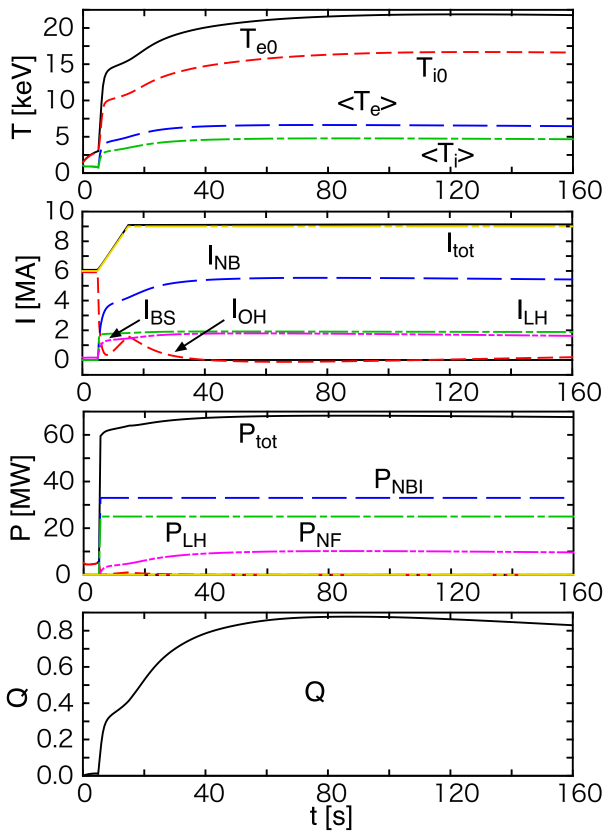
Quasi-Steady State Operational Scenario

- $I_p = 6 \rightarrow 9$ MA for 10 s, Negative shear profile, $I_{OH} \sim 0$

CDBM

$\beta_N = 1.2$

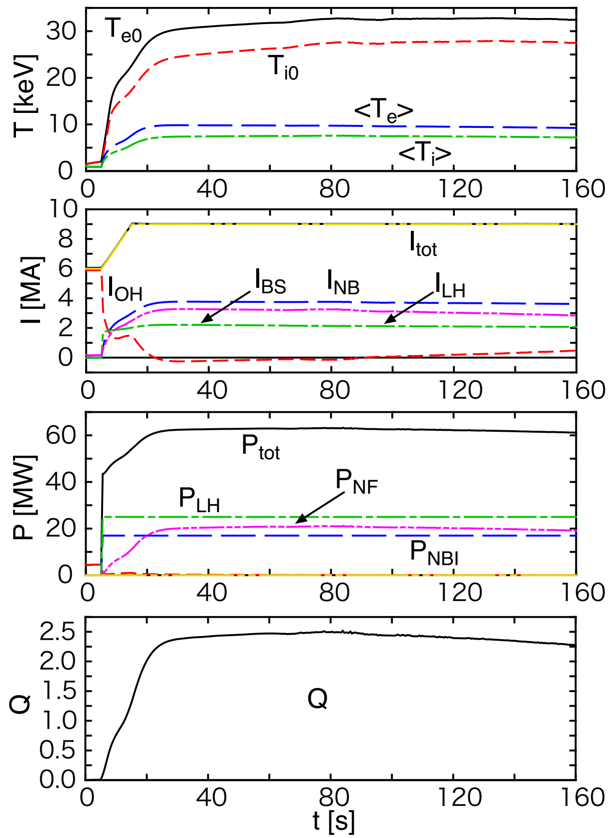
$\tau_E = 3.0$ s

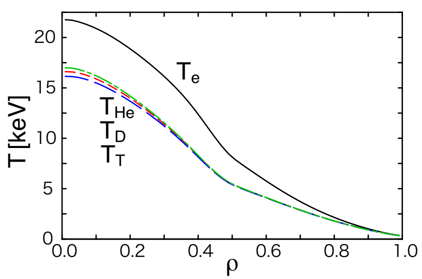


CDBM05

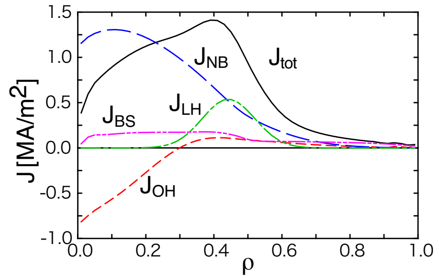
$\beta_N = 1.55$

$\tau_E = 3.2$ s

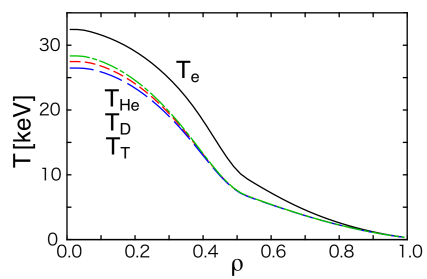




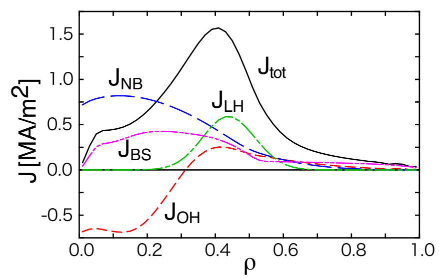
$P_{NB} = 35$ MW



$P_{LH} = 30$ MW



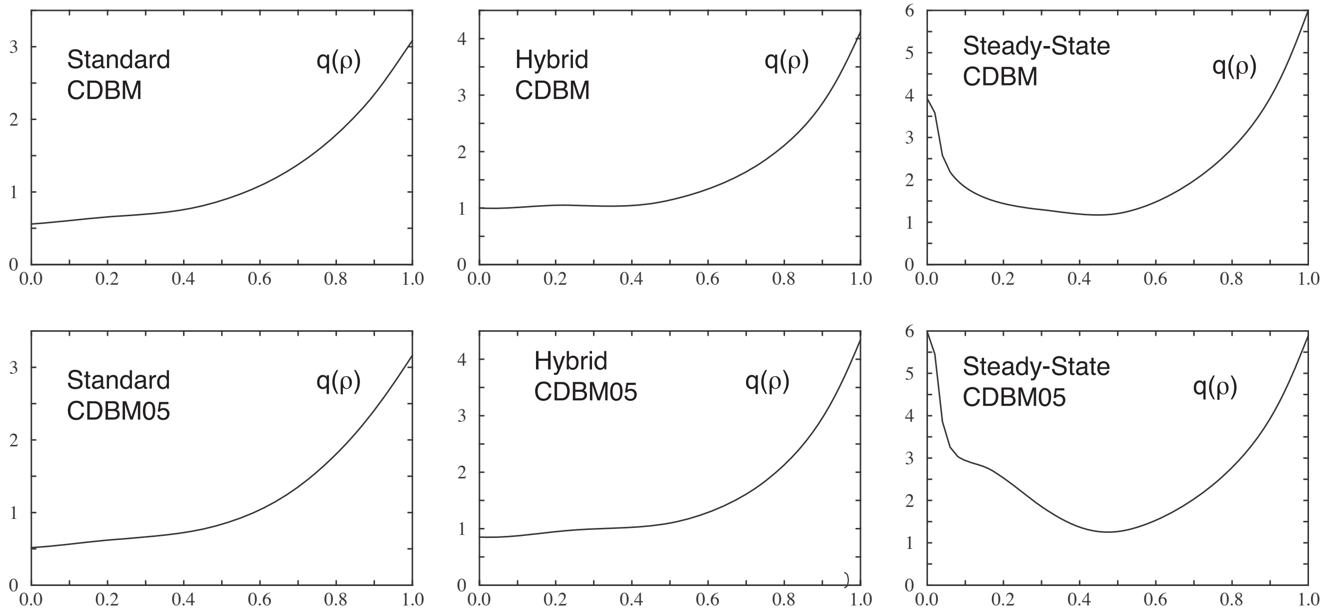
$P_{NB} = 17$ MW



$P_{LH} = 25$ MW

q Profiles of Previous Shots

Standard **Hybrid** **Steady State**



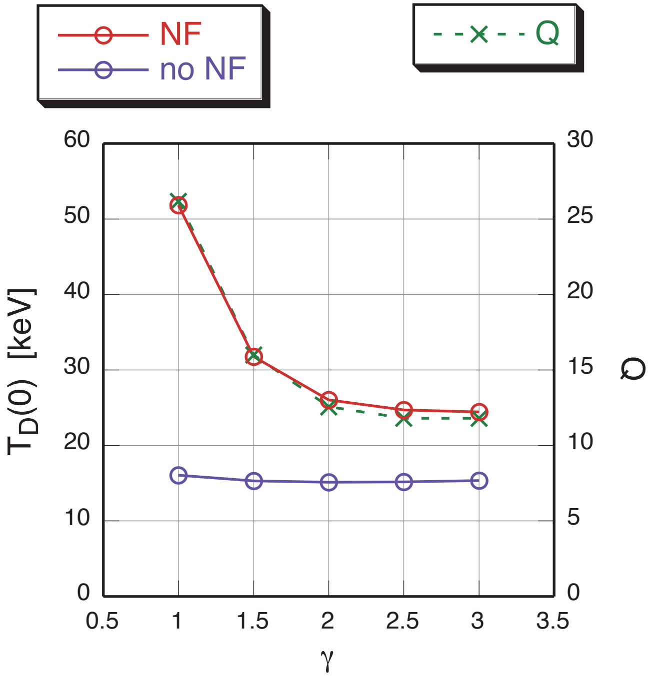
- Control of current profile in the hybrid operation requires more improvement to keep $q(0) > 1$.
- Performance of the quasi steady-state operation will be improved if the H-mode plasma edge (edge transport barrier) are included. .

Dependence on Initial Current Profile

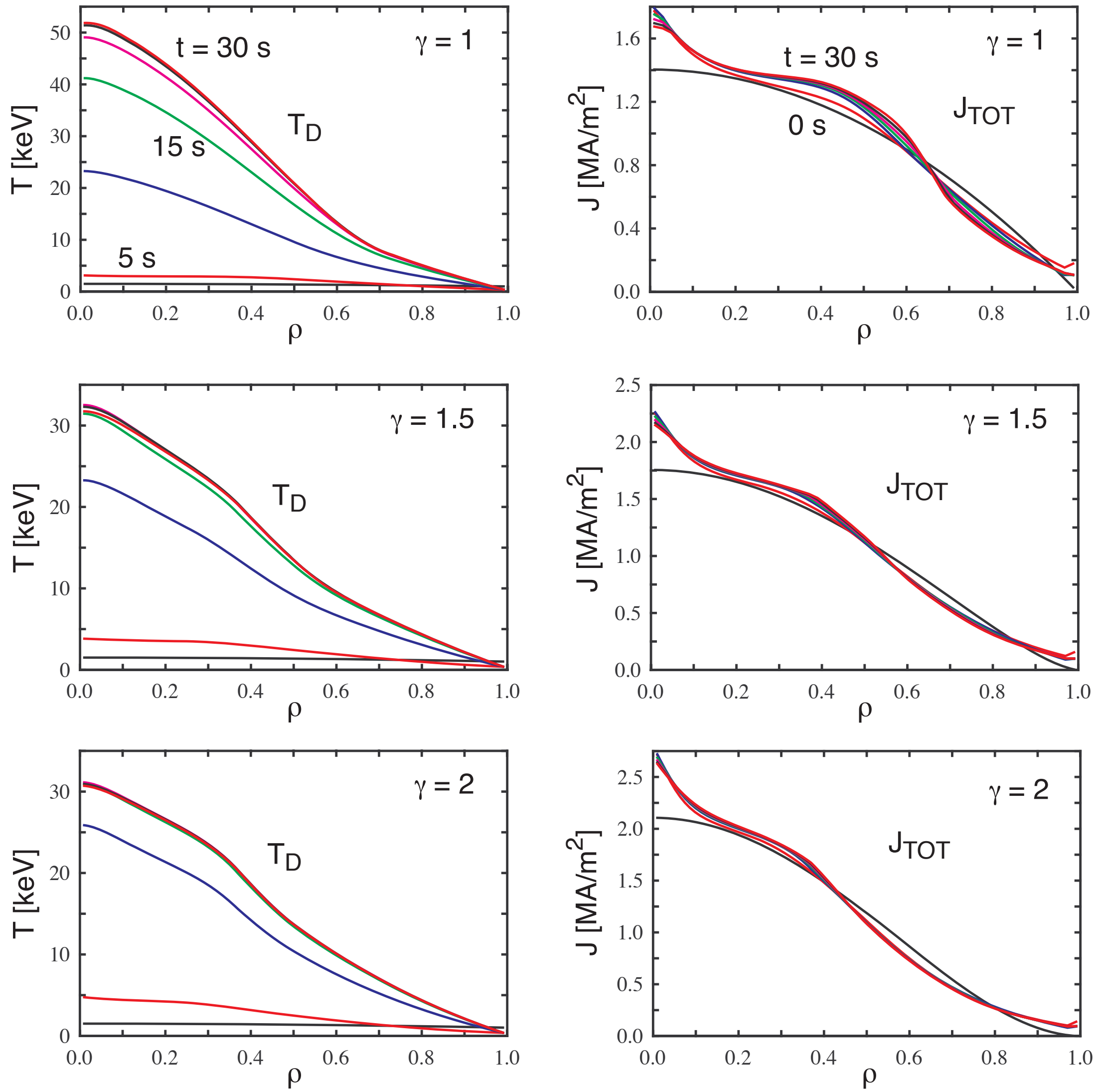
- **Initial current profile**

$$j(\rho) = j_0(1 - \rho^2)^\gamma$$

  - **Broader initial profile**
  - **Current profile shrink**
  - **ITB formation**



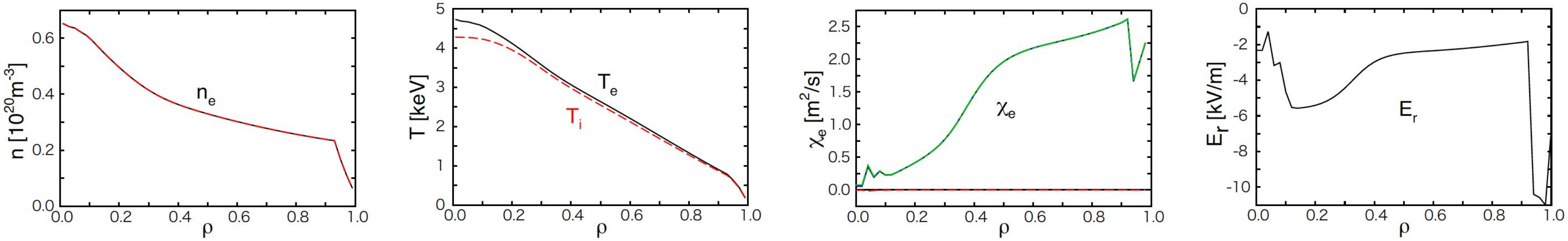
γ Dependence of $T(\rho)$ amnd $j(\rho)$



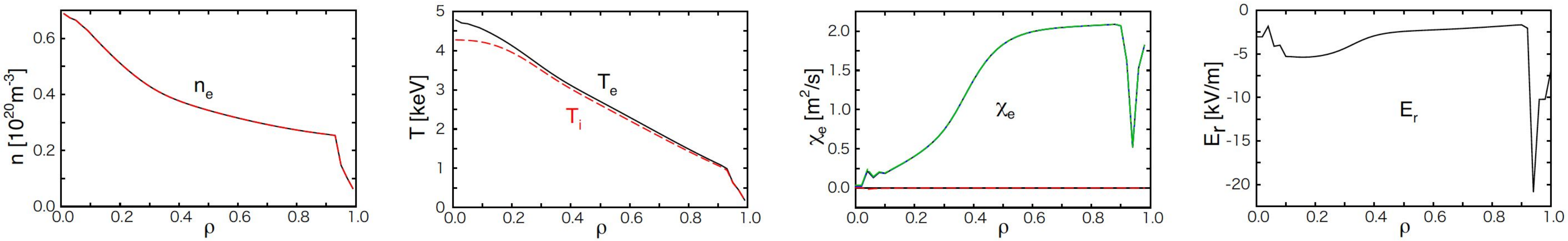
Simple ETB Model Including $E \times B$ Rotation Shear

- **Simple ETB mode**: **to be improved soon**
  - CDBM05 transport model; $D = 0.3\chi$
  - χ is reduced to 1/10 in the region $0.93 < \rho < 1$.
  - NBI heating: 10 MW

w/o $E \times B$ shear effect



w/ $E \times B$ shear effect



Summary

- The CDBM05 transport model including the effect of elongation has shown better agreement with the L and H mode data in the ITPA profile database than the previous CDBM model and other models.

- Time-dependent 1-1/2D thermal transport simulations of ITER plasmas with the CDBM05 model predict desired performance of standard, hybrid, and steady state operations.

- Initial current profile may strongly affect the plasma performance even in the standard H-mode operation.

- **Work in progress**
  - Prepartion for hybrid simulation with various transport models: GLF23, CDBM05, Weiland, IFS-PPPL and others.
  - More consistent heating and current modeling
  - Edge barrier modeling

Modeling of ETB Formation

- **Transport Simulation including Core and SOL Plasmas**
  - **Role of Separatrix**
    — Closed magnetic surface $\Longleftrightarrow$ Open magnetic field line
    — Difference of dominant transport process
  - **Radial Electric Field**
  - **Poloidal rotation, Toroidal rotation**
  - **Atomic Processes**

- **1D Transport code** (TASK/TX) *Fukuyama et al. PPCF (1994)*
  - **Two fluid equation for electrons and ions**
    — Flux surface averaged
    — Coupled with Maxwell equation
    — Neutral diffusion equation
  - **Neoclassical transport**
  - **Turbulent transport**
    — Current diffusive ballooning mode
    — Ambipolar diffusion through poloidal momentum transfer
    — Thermal diffusivity, Perpendicular viscosity

Model Equation (1)

- **Fluid equations** (electrons and ions)

$$\frac{\partial n_s}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r}(r n_s u_{sr}) + S_s$$

$$\frac{\partial}{\partial t}(m_s n_s u_{sr}) = -\frac{1}{r}\frac{\partial}{\partial r}(r m_s n_s u_{sr}^2) + \frac{1}{r} m_s n_s u_{s\theta}^2 + e_s n_s (E_r + u_{s\theta} B_\phi - u_{s\phi} B_\theta) - \frac{\partial}{\partial r} n_s T_s$$

$$\frac{\partial}{\partial t}(m_s n_s u_{s\theta}) = -\frac{1}{r^2}\frac{\partial}{\partial r}(r^2 m_s n_s u_{sr} u_{s\theta}) + e_s n_s (E_\theta - u_{sr} B_\phi) + \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^3 n_s m_s \mu_s \frac{\partial}{\partial r}\frac{u_{s\theta}}{r}\right)$$

$$+F_{s\theta}^{\mathrm{NC}} + F_{s\theta}^{\mathrm{C}} + F_{s\theta}^{\mathrm{W}} + F_{s\theta}^{\mathrm{X}} + F_{s\theta}^{\mathrm{L}}$$

$$\frac{\partial}{\partial t}\left(m_s n_s u_{s\phi}\right) = -\frac{1}{r}\frac{\partial}{\partial r}(r m_s n_s u_{sr} u_{s\phi}) + e_s n_s (E_\phi + u_{sr} B_\theta) + \frac{1}{r}\frac{\partial}{\partial r}\left(r n_s m_s \mu_s \frac{\partial}{\partial r} u_{s\phi}\right)$$

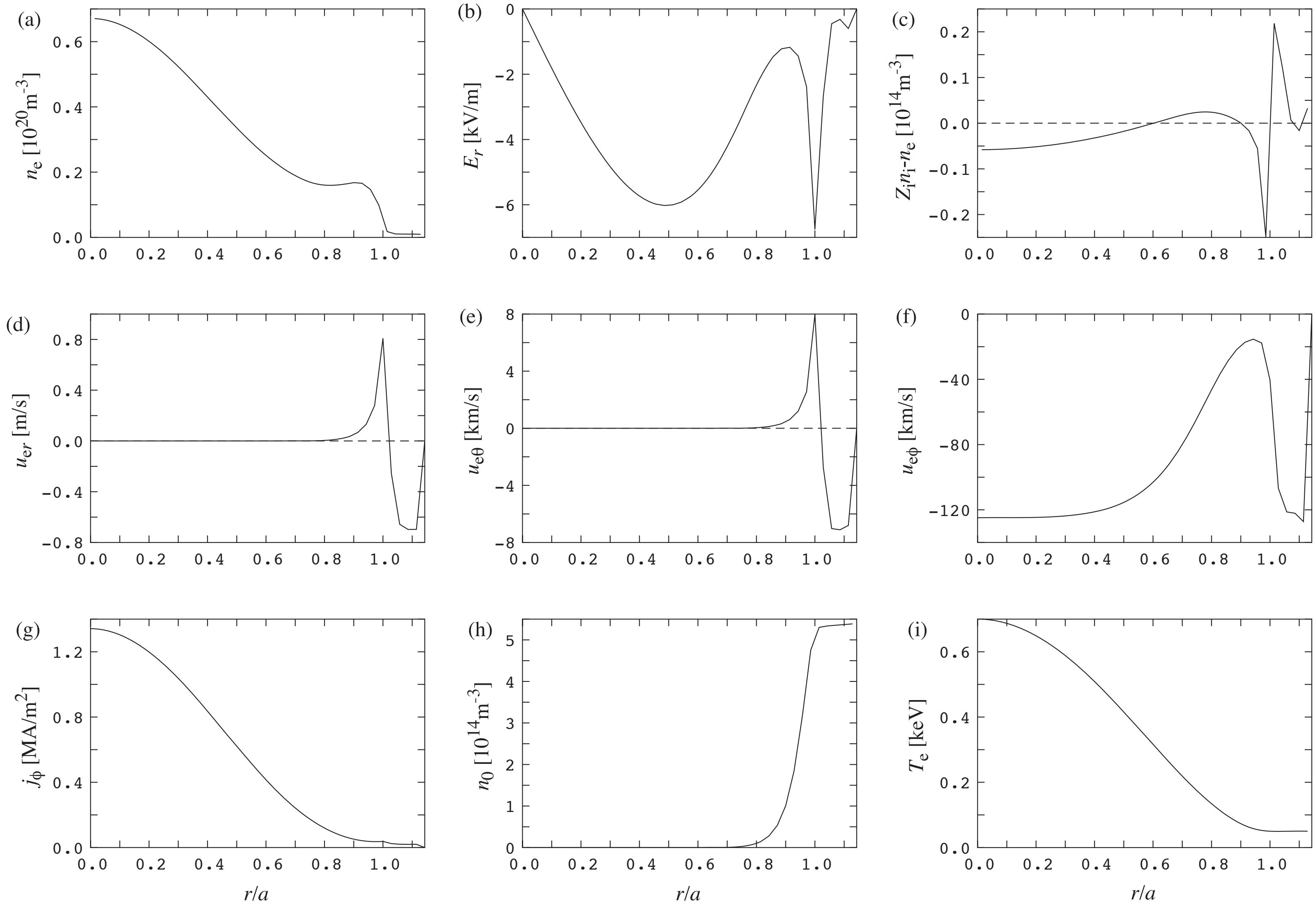
$$+F_{s\phi}^{\mathrm{C}} + F_{s\phi}^{\mathrm{W}} + F_{s\phi}^{\mathrm{X}} + F_{s\phi}^{\mathrm{L}}$$

$$\frac{\partial}{\partial t}\frac{3}{2} n_s T_s = -\frac{1}{r}\frac{\partial}{\partial r} r\left(\frac{5}{2} u_{sr} n_s T_s - n_s \chi_s \frac{\partial}{\partial r} T_{\mathrm{e}}\right) + e_s n_s (E_\theta u_{s\theta} + E_\phi u_{s\phi})$$

$$+P_s^{\mathrm{C}} + P_s^{\mathrm{L}} + P_s^{\mathrm{H}}$$

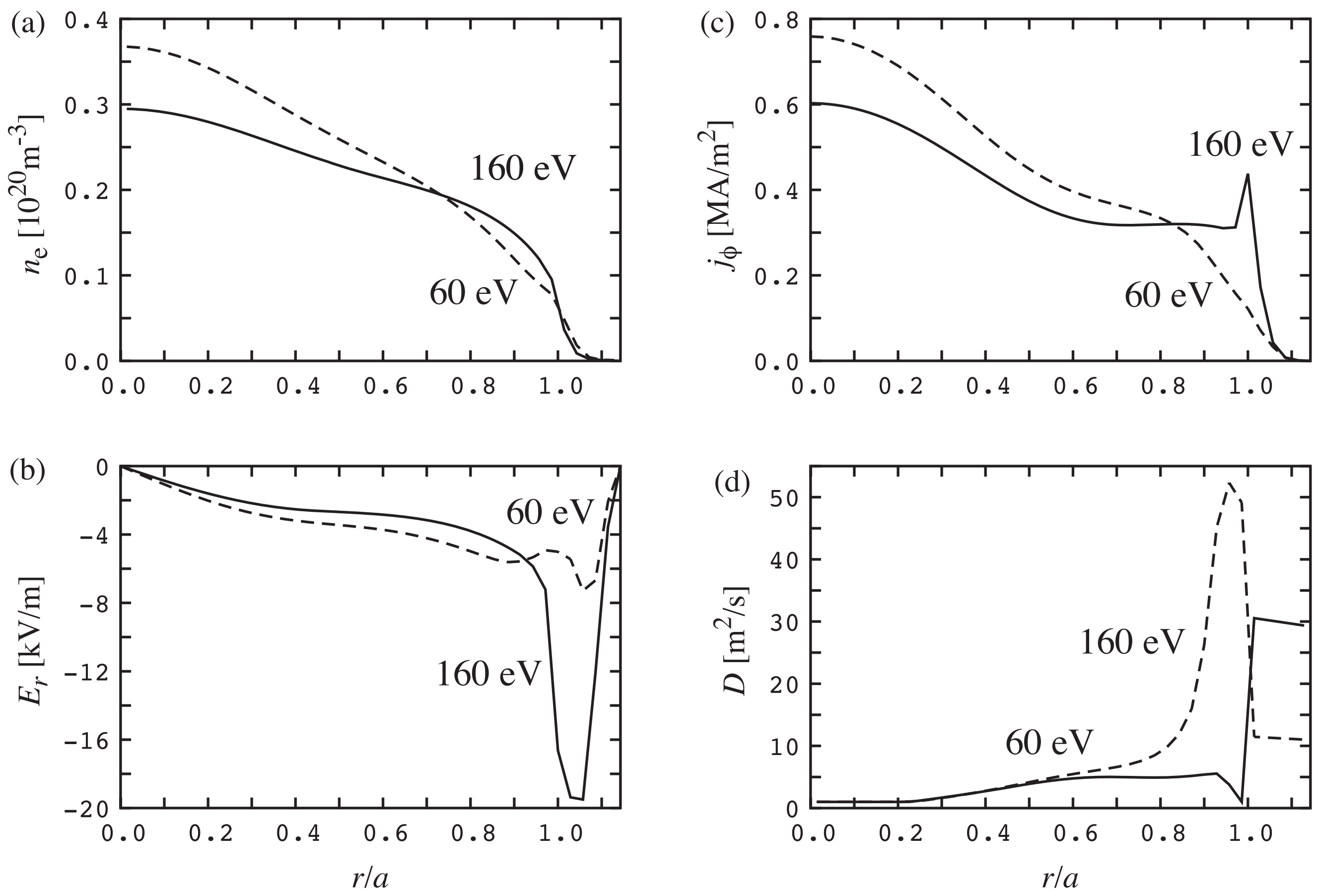
Typical Profiles without Turbulent Transport

n_e	E_r	$n_\mathrm{i} - n_\mathrm{e}$
$u_{\mathrm{e}r}$	$u_{\mathrm{e}\theta}$	$u_{\mathrm{e}\phi}$
j_ϕ	n_0	T_e

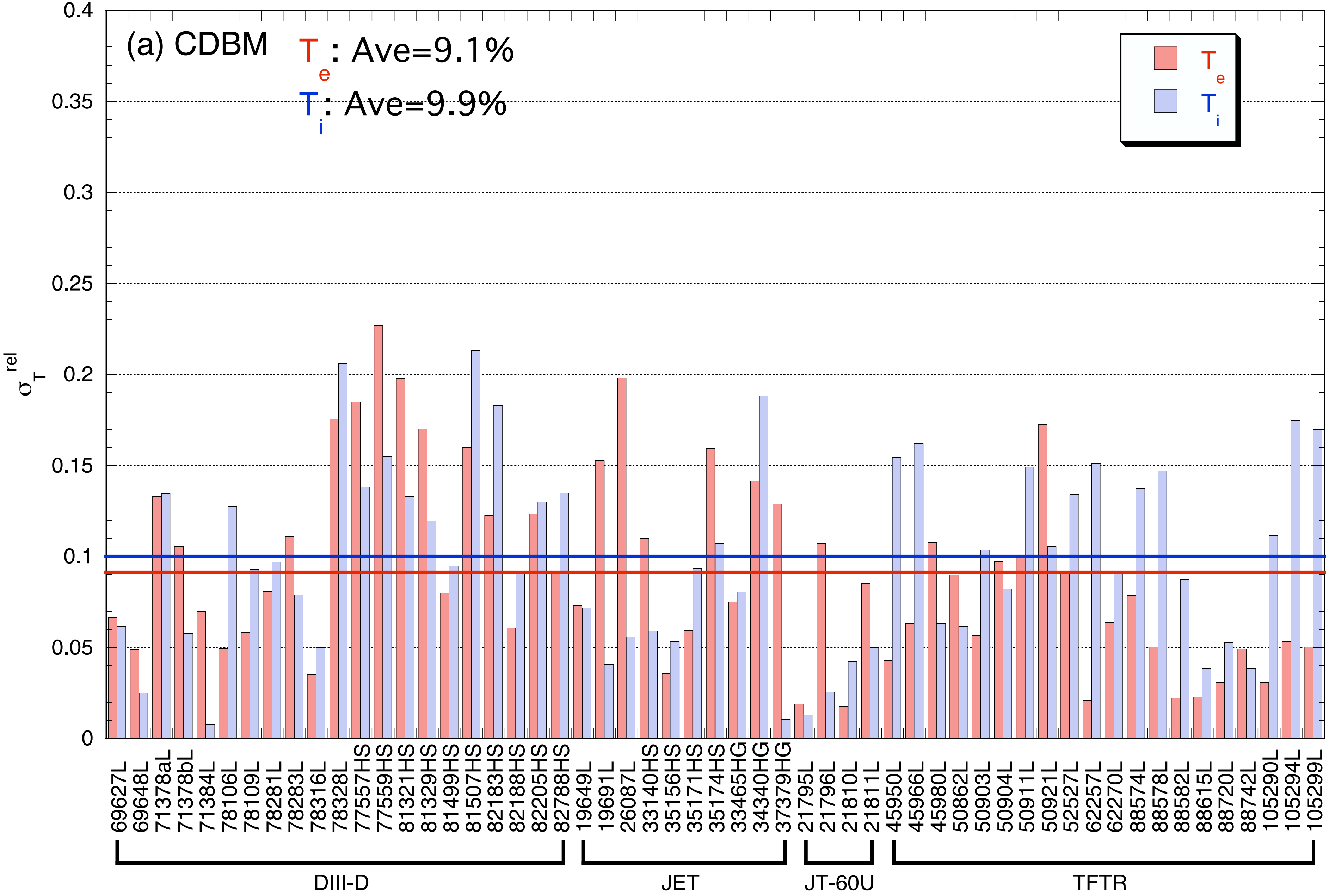


ETB formation

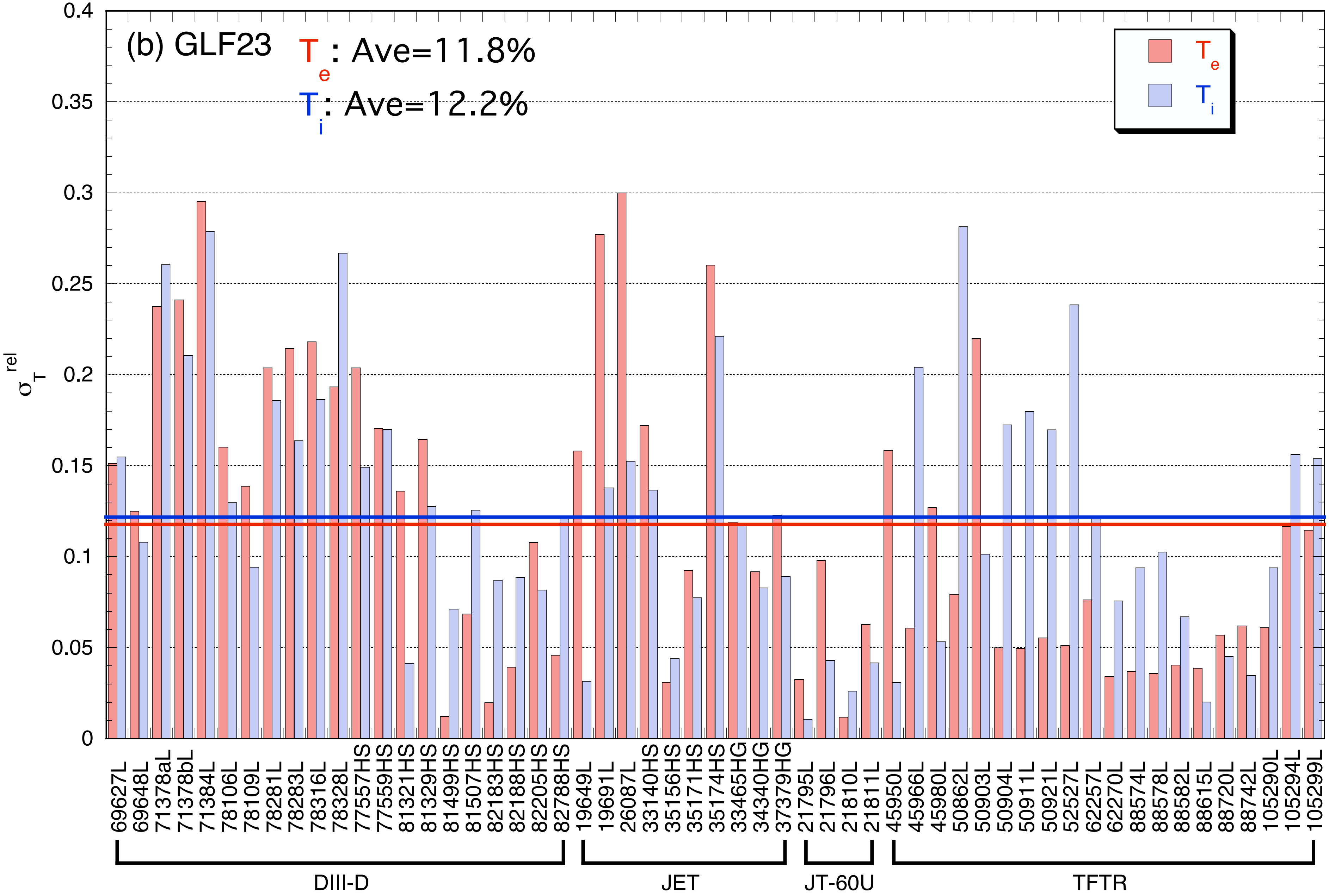
Edge Temperature Dependence



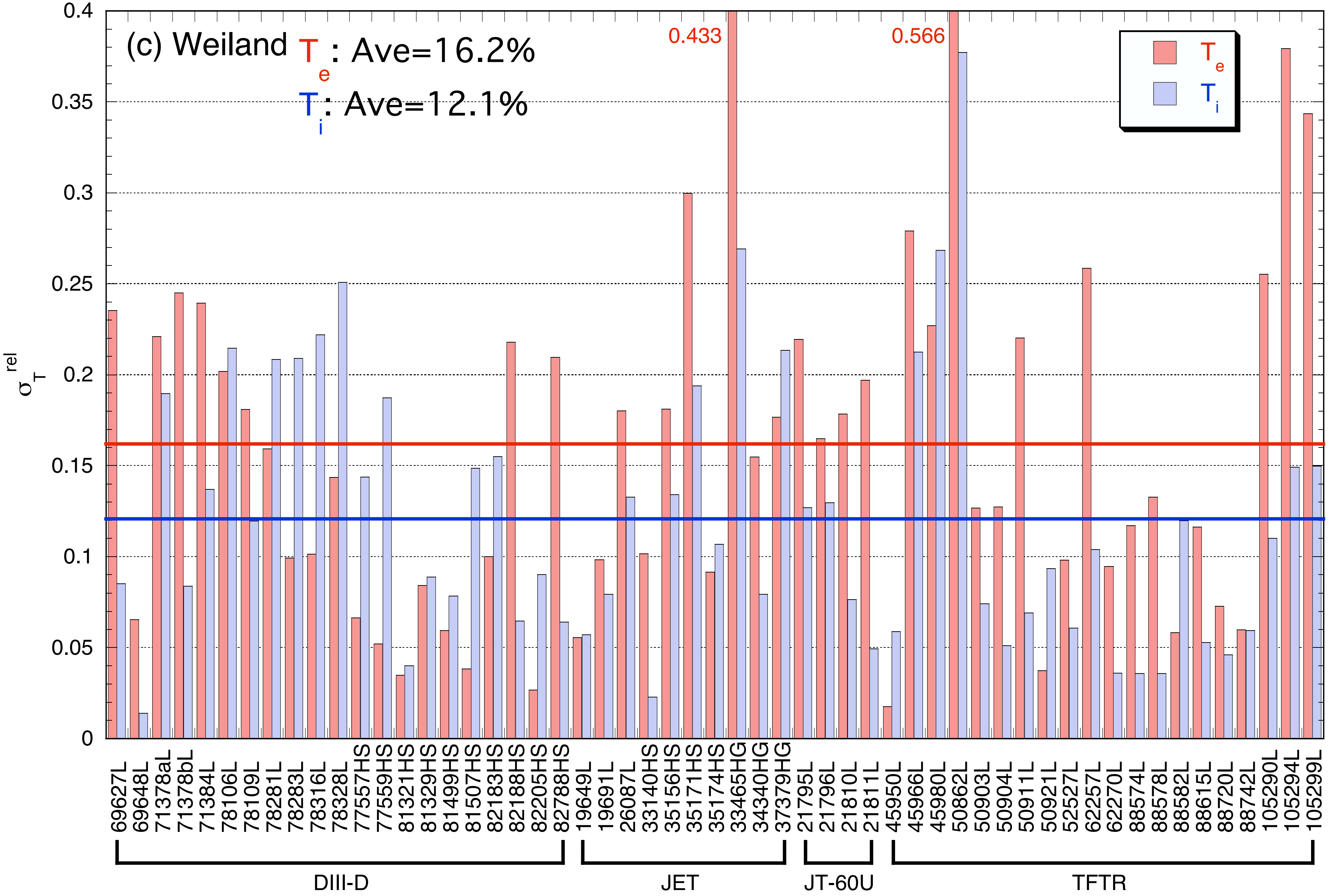
Relative RMS Error for Temperature Profiles (CDBM)



Relative RMS Error for Temperature Profiles (GLF23)



Relative RMS Error for Temperature Profiles (Weiland)



Relative RMS Error for Temperature Profiles (CDBM05)