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Recent Progress of Transport Simulation by TASK code

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Contents

- **TASK/TR: Diffusive Transport Module**
  - CDBM05: Improvement of CDBM Transport Model
  - Transport Simulation of ITER with CDBM05 Model
- **TASK/TX: Dynamical Transport Module**
  - Dynamical Transport Equation
  - Density Profile Modification Due to NBI Injection
- **Summary**

The Way of Simulation

- **Neoclassical Transport Models**: **NCLASS**
- **Turbulent Transport Models**: **CDBM, GLF23, Weiland**
- Solving thermal transport equations with **fixed density profile** using stationary experimental profiles from ITPA profile database.
  - 1D: R, a, I_p, B_t, κ, ϕ_a
  - 2D: $T_{\mathrm{e,i}}$, $n_{\mathrm{e,bulk,imp}}$, Z_{eff}, q, j, Q_{heating}, $S_{\mathrm{NB,wall}}$, V_{rot}, Metrics (Geometric quantities)
- **Particle diffusivity is included through a particle flux calculated from $S_{\mathrm{NB,wall}}$.**
- Calculating the core region of $\rho \leq 0.9$ excluding the effect of the edge, ρ normalized radius.
- Diagonal turbulent transport coefficient is set to be zero if it becomes negative.
- **Additional conditions:**
  - CDBM: The effect of $\boldsymbol{E} \times \boldsymbol{B}$ shearing stabilization is not included.

    ω_{E1} and κ_* are assumed to be zero in the formula of F.
  - GLF23: Toroidal rotation velocity (V_{tor}) is provided from exp. data.
  - Neoclassical heat convection and conduction are considered.

Conditions for Comparison

- **Initial temperature profiles and boundary conditions at $\rho = 0.9$ during the computation are given by exp. data.**
- A current density profile is obtained from the database if available, otherwise it is produced using a safety factor profile.
- Comparison of resulting $T_{\mathrm{e,i}}$ profiles with experimental data in each discharge.
  - Compared at a fully relaxed time (typically $0.5\ \mathrm{s}$).
- Choosing discharges based on **"ITER Physics Basis: Chapter 2**[3] **[8.4 Results of one dimensional modelling tests]"**
- **55 discharges composed of 38 L-mode, 14 H-mode with small ELMs and 3 H-mode with giant ELMs discharges**
- **Six figures of merit** in the following were calculated.

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[3] 1999 *Nucl. Fusion* **39** 2175-2249

Definition of Figures of Merit

- **Mean and mean square deviations of the incremental stored energy**

$$\langle R_\mathrm{W}\rangle = \frac{1}{N}\sum_i^N R_{\mathrm{W}i}, \quad \sigma_\mathrm{W} = \sqrt{\frac{1}{N}\sum_i^N R_{\mathrm{W}i}^2}, \quad R_{\mathrm{W}i} = \frac{W_{\mathrm{sim},i}^\mathrm{inc}}{W_{\exp,i}^\mathrm{inc}} - 1$$

where $W^\mathrm{inc} = \dfrac{3}{2}\displaystyle\int_0^{0.9}[n_\mathrm{e}(\rho)\tilde{T}_\mathrm{e}(\rho) + n_\mathrm{i}(\rho)\tilde{T}_\mathrm{i}(\rho)]V'\mathrm{d}\rho,\ \tilde{T}(\rho) = T(\rho) - T(0.9)$

N: the number of discharges

- **Mean offset and mean standard deviation of the temperature for $s = \mathrm{e}, \mathrm{i}$**

$$\mathrm{MOFF_s} = \frac{1}{N}\sum_i^N \left[\frac{\sum_\rho^M [T_\mathrm{sim,s}(\rho) - T_\mathrm{exp,s}(\rho)]}{\sqrt{M\sum_\rho^M T_\mathrm{exp,s}^2(\rho)}}\right], \qquad (0.2 \le \rho \le 0.9)$$

$$\mathrm{MSTD_s} = \frac{1}{N}\sum_i^N \left[\sqrt{\frac{\sum_\rho^M [T_\mathrm{sim,s}(\rho) - T_\mathrm{exp,s}(\rho)]^2}{\sum_\rho^M T_\mathrm{exp,s}^2(\rho)}}\right], \qquad (0.2 \le \rho \le 0.9)$$

M: the number of radial meshes

Elongation Effect for CDBM model

- From the figures of “Dependence on Devices”, it is found that **the predictions by the CDBM model are generally overestimated for TFTR and underestimated for others; this behavior would be attributed to the elongation effect.**
- The original CDBM model was developed on the assumption of a circular cross section plasma.
- We therefore **include the dependence on the elongation effect in the formula of F** along with the reference[4] as follows:

$$F \propto \left(\frac{2\kappa^{1/2}}{\kappa^2 + 1} \right)^{3/2} .$$

- This dependence clearly tends to decrease F and thus suppress the transport when the elongation κ is above unity (typically 0.65 when $\kappa = 1.5$).

Results

- **Large negative deviations for DIII-D H-mode shots are to some extent improved, but the predictions for some discharges (i.e. DIII-D L-mode and JET HSELM) are overestimated more than needs.**
- **On the whole, σ_{W} is improved from 23.5% to 20.8%.**

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[4] Yagi M *et al* 1997 *J. Phys. Soc. Japan* **66** 379

CDBM Transport Model: CDBM05

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

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

Magnetic shear $s \equiv \dfrac{r}{q} \dfrac{\mathrm{d}q}{\mathrm{d}r}$

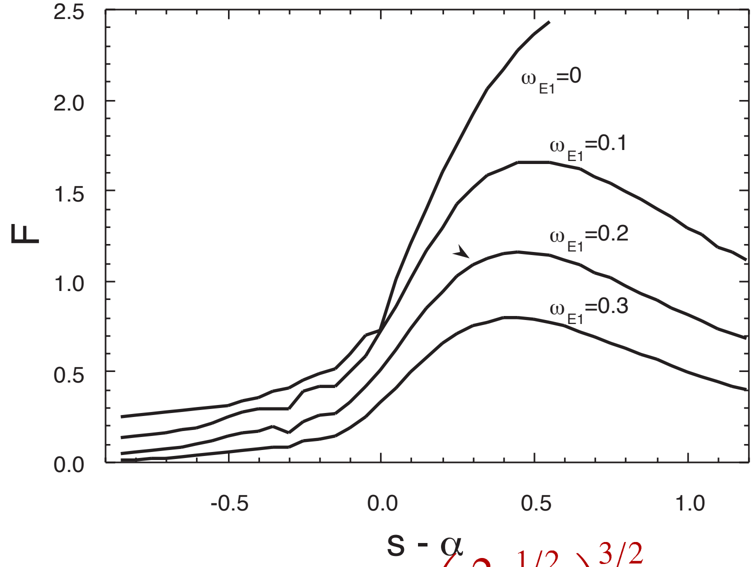
Pressure gradient $\alpha \equiv -q^2 R \dfrac{\mathrm{d}\beta}{\mathrm{d}r}$

Elongation $\kappa \equiv b/a$

$E \times B$ rotation shear $\omega_{\mathrm{E1}} \equiv \dfrac{r^2}{s v_{\mathrm{A}}} \dfrac{\mathrm{d}}{\mathrm{d}r} \dfrac{E}{rB}$

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

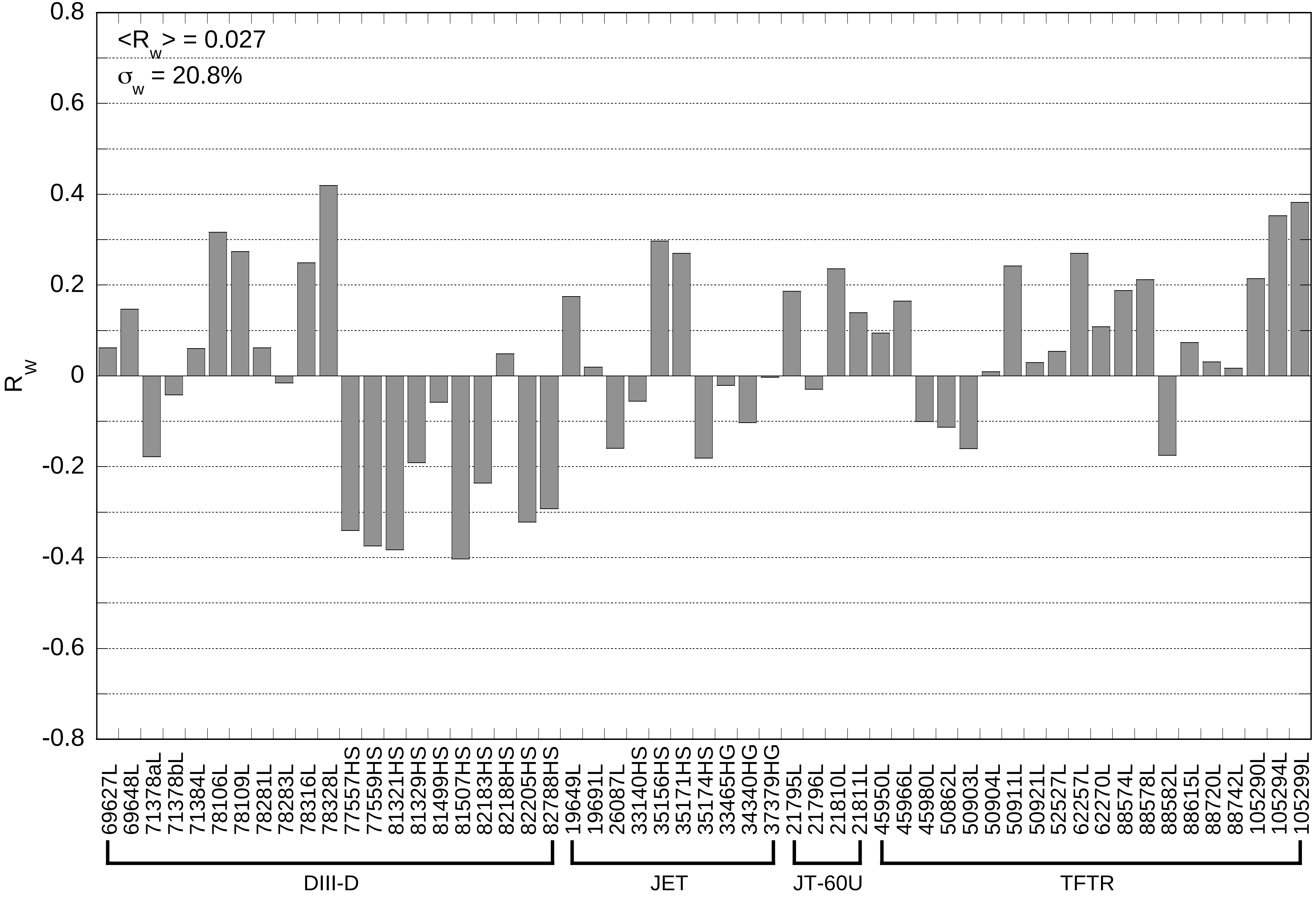
$s - \alpha$ dependence of $F(s, \alpha, \kappa, \omega_{\mathrm{E1}})$



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

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

Deviation of Stored Energy (CDBM with elongation)



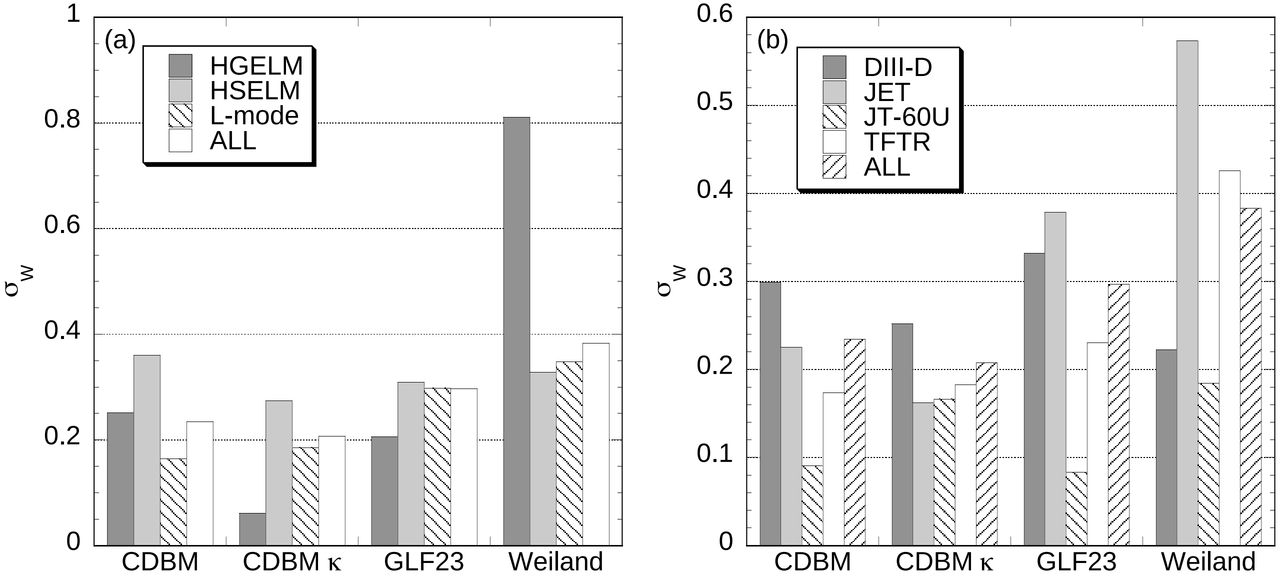
Comparison of the five transport models with respect to σ_W

- Comparing the five transport models with respect to σ_W in each operation mode and each device.
- **Obviously the best result is obtained by the CDBM model with the elongation effect (CDBM κ) in 55 discharges.**

HGELM · · · CDBM κ
HSELM · · · CDBM κ
L-mode · · · CDBM

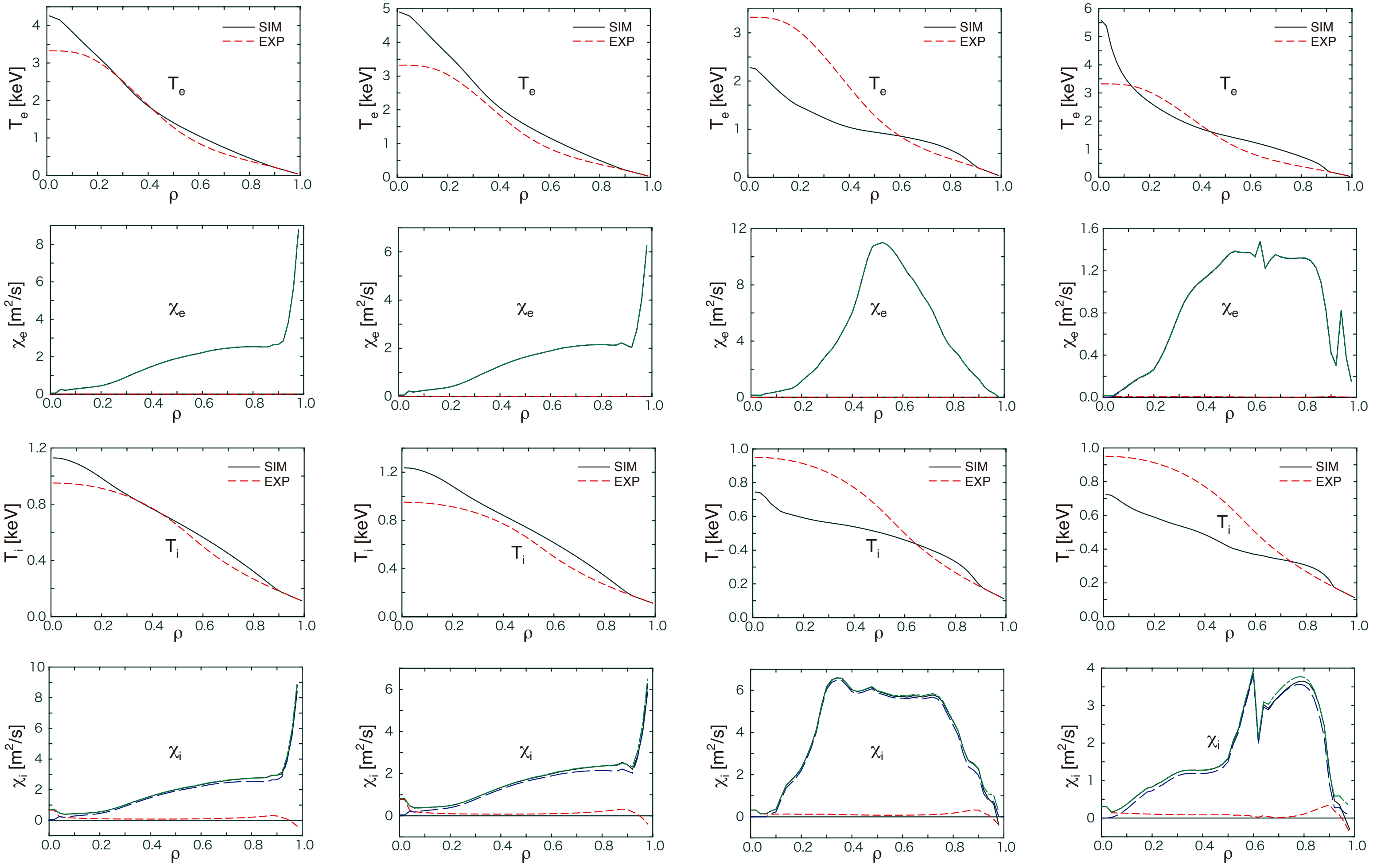
DIII-D · · · Weiland
JET · · · CDBM κ
JT-60U · · · GLF23
TFTR · · · CDBM

- Some shots on JET HGELM and TFTR L-mode impede total performance for the Weiland model, but the results for other shots are comparable to other models'.

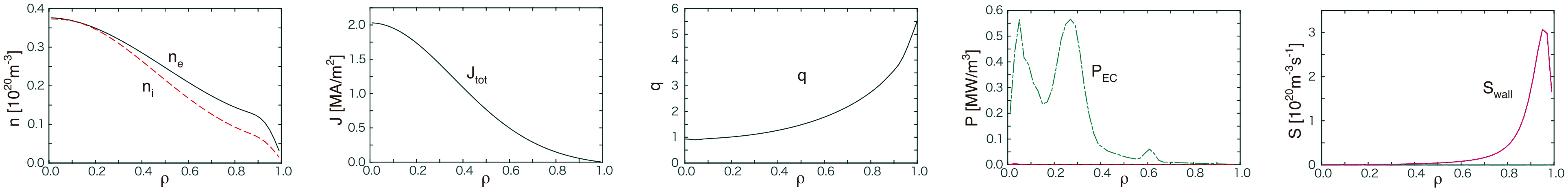


DIII-D #78316 (L-mode, ECH and ICH heatings)

CDBM | CDBM κ | GLF23 | Weiland



Common Profiles



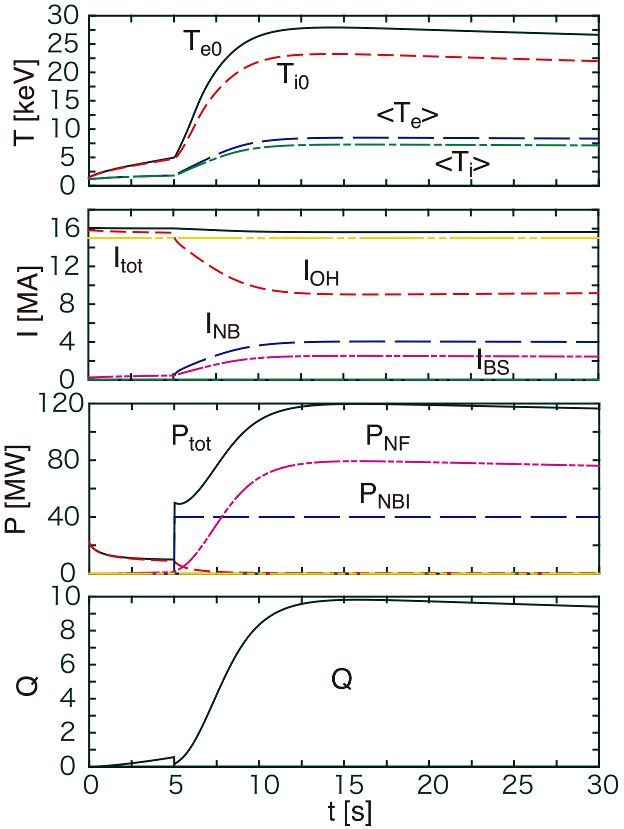
ITER Simulations

- **Using the CDBM and modified CDBM (CDBM05) models**
  - Both models can reproduce temperature profiles for L-mode and H-mode discharges.
  - 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.

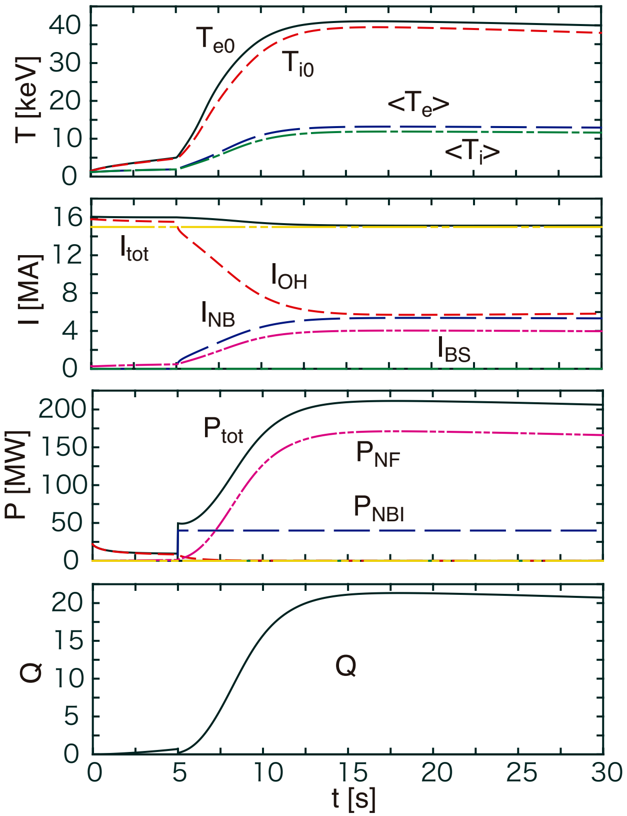
High Q Operational Scenario

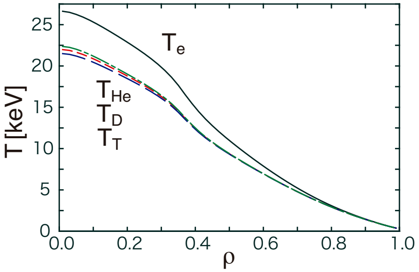
- Large plasma current: $I_p = 15$ MA, On-axis heating: $P_{NB} = 40$ MW
- Positive shear profile, Relatively large f_{OH}

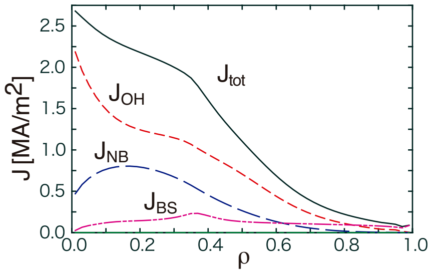
CDBM

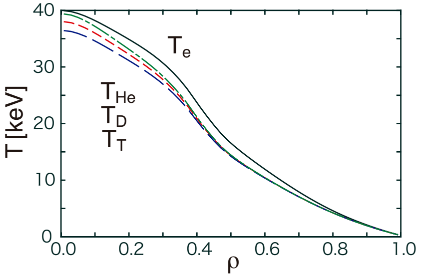


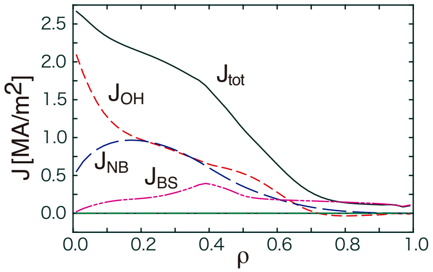
CDBM05







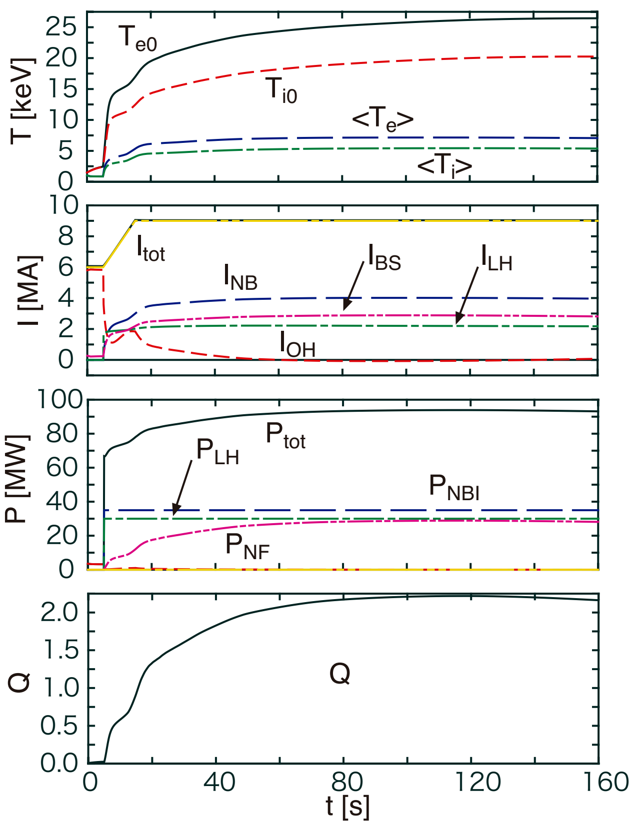




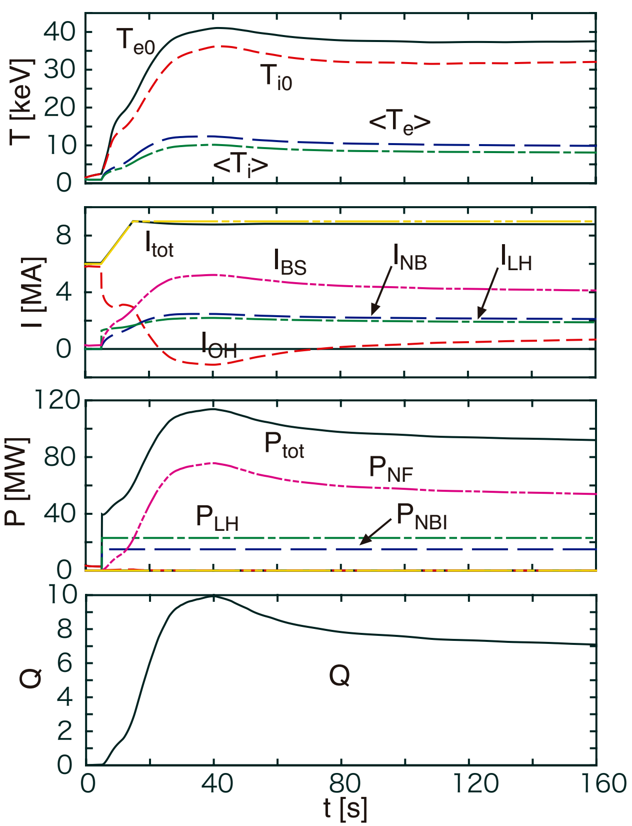
Quasi-Steady State Operational Scenario

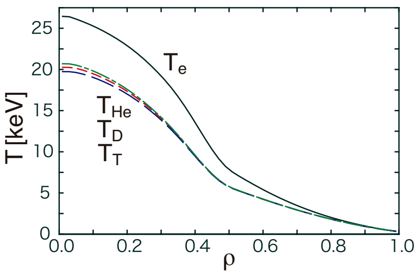
- $I_p = 6 \rightarrow 9$ MA for 10 s, Negative shear profile, $I_{OH} \sim 0$

CDBM

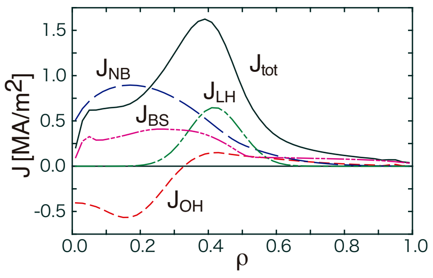


CDBM05

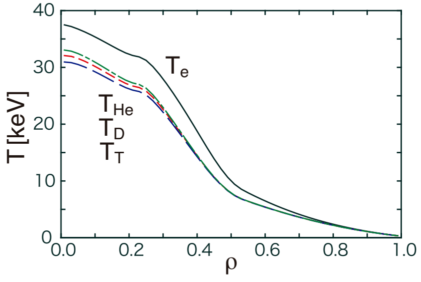




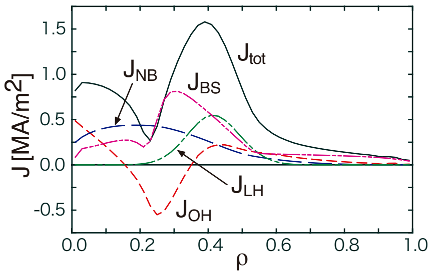
P_{NB} = 35 MW



P_{LH} = 30 MW



P_{NB} = 15 MW



P_{LH} = 23 MW

Dynamical Transport Equation

- **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)

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

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

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

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

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

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

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

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

Neoclassical Transport Model

- **Neoclassical transport**
  - Viscosity force arises when plasma rotates in the poloidal direction.
  - Banana-Plateau regime

$$F_{s\theta}^{\mathrm{NC}} = -\sqrt{\pi} q^2 n_s m_s \frac{v_{\mathrm{T}s}}{qR} \frac{\nu_s^*}{1+\nu_s^*} u_{s\theta}$$

$$\nu_{\mathrm{s}}^* \equiv \frac{\nu_s qR}{\epsilon^{3/2} v_{\mathrm{T}s}}$$

- **This poloidal viscosity force induces**
  - Neoclassical radial diffusion
  - Neoclassical resistivity
  - Bootstrap current
  - Ware pinch

Turbulent Transport Model

- **Turbulent Diffusion**
  - Poloidal momentum exchange between electron and ion through the turbulent electric field
  - Ambipolar flux (electron flux = ion flux)

$$F^{\mathrm{W}}_{\mathrm{i}\theta} = - F^{\mathrm{W}}_{\mathrm{e}\theta}$$

$$= - ZeB_\phi n_\mathrm{i} D_\mathrm{i} \left[-\frac{1}{n_\mathrm{i}}\frac{dn_\mathrm{i}}{dr} + \frac{Ze}{T_\mathrm{i}} E_r - \langle \frac{\omega}{m} \rangle \frac{ZeB_\phi}{T_\mathrm{i}} - \left(\frac{\mu_\mathrm{i}}{D_\mathrm{i}} - \frac{1}{2} \right) \frac{1}{T_\mathrm{i}} \frac{dT_\mathrm{i}}{dr} \right]$$

- **Perpendicular viscosity**
  - Non-ambipolar flux (electron flux ≠ ion flux): $\mu_s = \text{constant} \times D$
- **Diffusion coefficient** (proportional to $|E|^2$)
  - Current-diffusive ballooning mode turbulence model

Model of Scrape-Off Layer Plasma

- **Particle, momentum and heat losses along the field line**
  - Decay time

$$\nu_\mathrm{L} = \begin{cases} 0 & (0 < r < a) \\ \dfrac{C_\mathrm{s}}{2\pi r R\{1 + \log[1 + 0.05/(r-a)]\}} & (a < r < b) \end{cases}$$

  - **Electron source term**

$$S_\mathrm{e} = n_0\langle\sigma_\mathrm{ion} v\rangle n_\mathrm{e} - \nu_\mathrm{L}(n_\mathrm{e} - n_\mathrm{e,div})$$

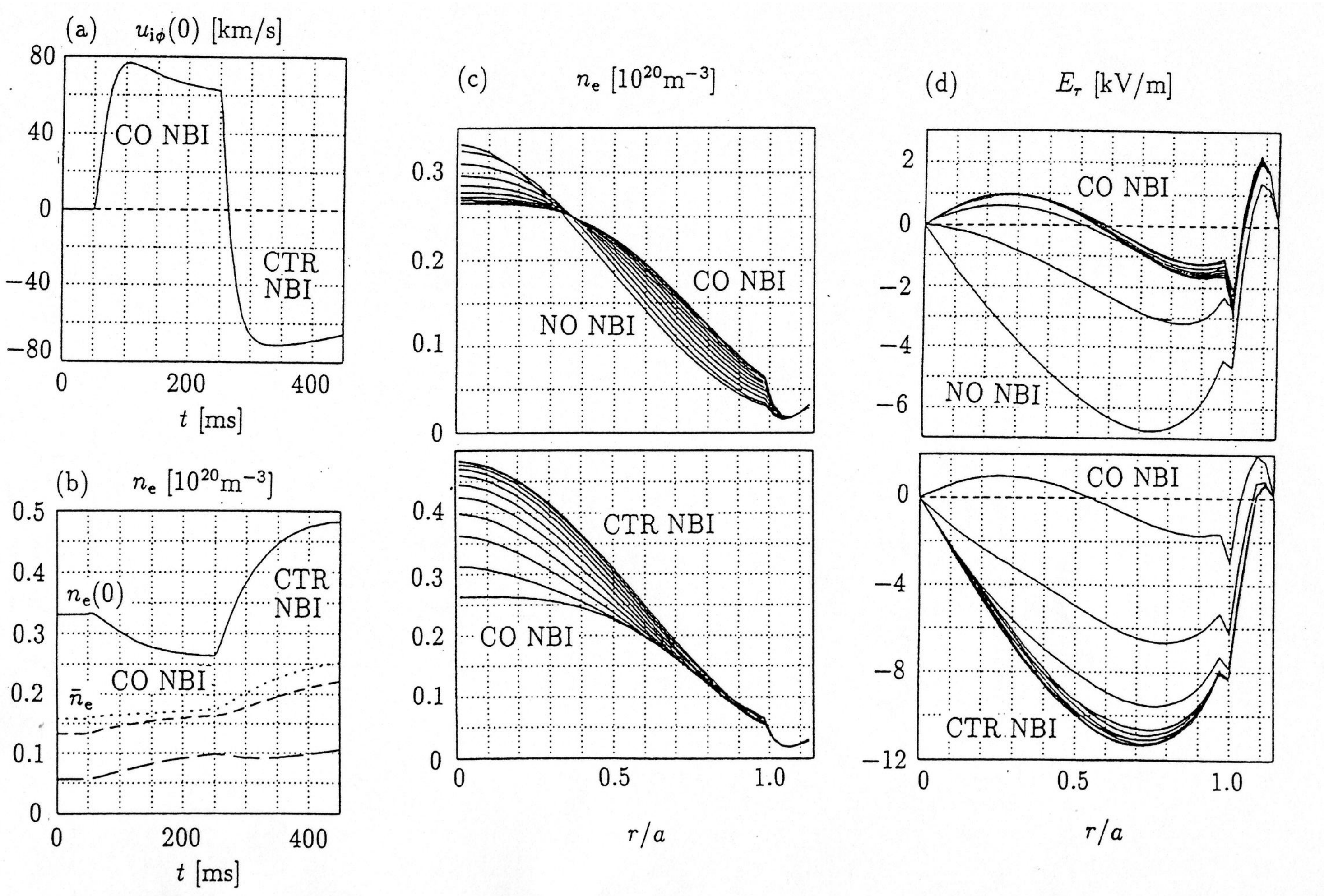
- **Recycling from divertor**
  - Recycling rate: $\gamma_0 = 0.8$
  - Neutral source

$$S_0 = \frac{\gamma_0}{Z_\mathrm{i}}\nu_\mathrm{L}(n_\mathrm{e} - n_\mathrm{e,div}) - \frac{1}{Z_\mathrm{i}} n_0\langle\sigma_\mathrm{ion} v\rangle n_\mathrm{e} + \frac{P_\mathrm{b}}{E_\mathrm{b}}$$

- **Gas puff from wall**

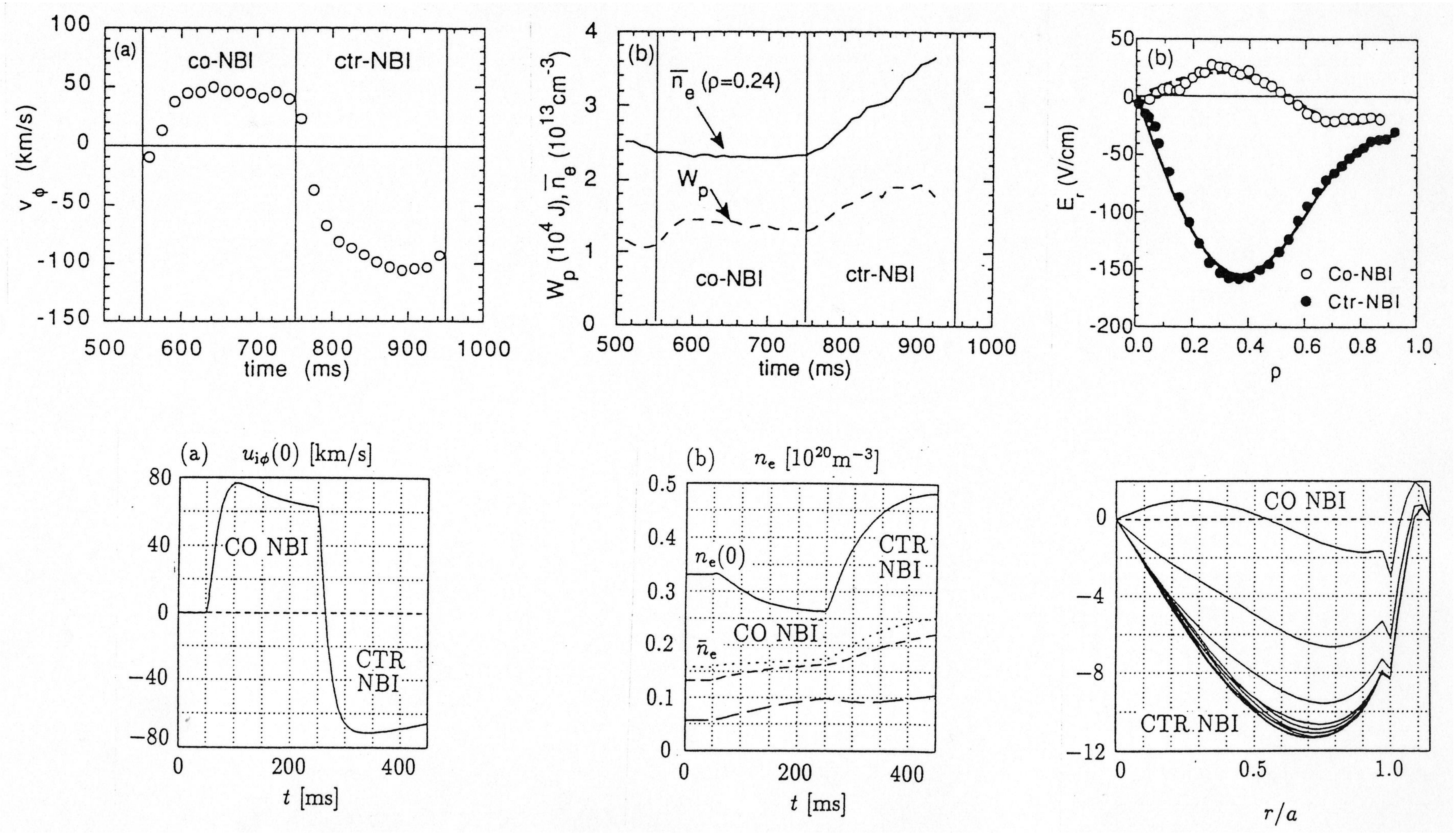
Simulation of plasma rotation and radial electric field

- **JFT-2M parameter**: NBI co-injection ⟶ counter-injection
- Toroidal rotation ⟹ Negative E_r ⟹ Density peaking
- **TASK/TX**: Particle Diffusivity: $0.3\,\mathrm{m^2/s}$, Ion viscosity: $10\,\mathrm{m^2/s}$



Comparison with JFT-2M Experiment

- **JFT-2M Experiment**: **Ida et al.: Phys. Rev. Lett. 68 (1992) 182**
- Good agreement with experimental observation



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.

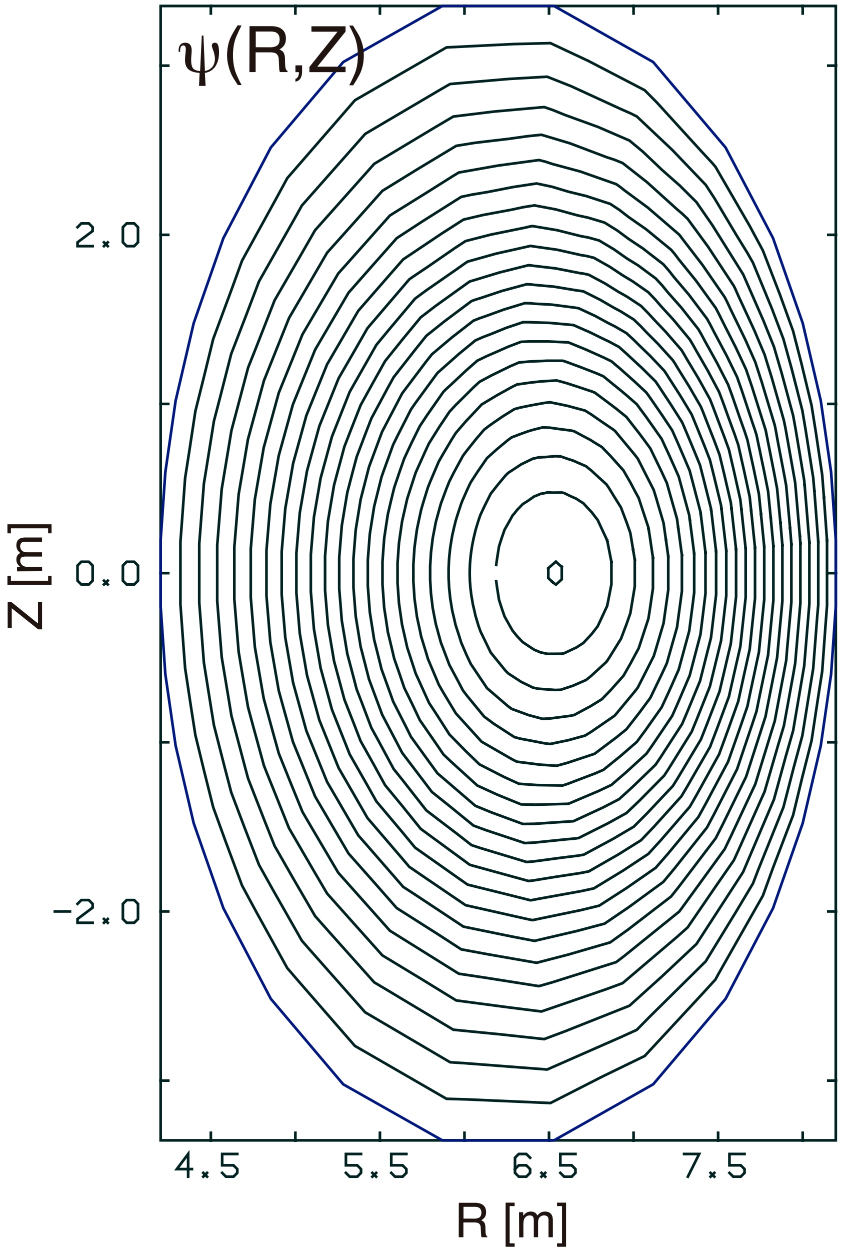
- Preliminary results of the 1-1/2D thermal transport simulation of ITER plasmas with the CDBM05 model predicts desired performance.

- Consistent analysis of the toroidal momentum input and particle transport was carried out with the dynamical transport equation which keeps the ion inertia terms and the radial electric field.

- To-Do List
  - Simulation of ITB formation using the ITB profile database
  - More consistent simulation of ITER plasma (particle transport, heating and current drive, radiation, impurities)
  - Improvement of turbulent viscosity model and flux-surface average of the dynamical transport equations

Configuration for High Q Operational Scenario

- $R = 6.2$ m
- $a = 2.0$ m
- $\kappa = 1.7$
- $\delta = 0$
- $B_\phi = 5.7$ T
- $I_\mathrm{p} = 15$ MA
- $n_{\mathrm{e,D,T,He}} = 1.0, 0.45, 0.45, 0.05\ \mathrm{m}^{-3}$ on-axis
- NBI
  - Position of deposition: $r = 0$ m
  - Width of deposition profile: $r_\mathrm{W} = 1.0$ m
  - Energy of NB particles: $E = 1.0$ keV
  - Tangential radius: $r_\mathrm{T} = 6.2$ m
  - Current drive efficiency: 1.0
  - Total power: $P_\mathrm{NB} = 40$ MW



Configuration for Quasi-Steady State Operational Scenario

- $R = 6.34$ m
- $a = 1.859$ m
- $\kappa = 1.857$
- $\delta = 0.434$
- $B_\phi = 5.3$ T
- $I_\mathrm{p} = 6$ MA
- $n_{\mathrm{e,D,T,He}} = 0.724, 0.326, 0.326, 0.036\ \mathrm{m}^{-3}$ on-axis
- NBI: same condition except $P_\mathrm{NB} = 35$ or 15 MW
- LHRF
  - Position of deposition: $r = 1.0$ m
  - Width of deposition profile: $r_\mathrm{W} = 0.8$ m
  - Tangential radius: $r_\mathrm{T} = 6.2$ m
  - Parallel refractive index: $N_{\|} = 2.0$
  - Total power: $P_\mathrm{NB} = 30$ or 23 MW