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Integrated Modeling of Steady State Scenarios for ITER Using the TASK Code

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Outline

1. Integrated Modeling code: TASK
2. Self-Consistent Full Wave Analysis of ICRF Waves
3. Beam Tracing of ECRF Waves
4. CDBM Transport Model
5. Analysis of ITER Steady-State Scenario
6. Summary

TASK Code

- **Transport Analysing System for TokamaK**
- **Features**
  - **A Core of Integrated Modeling Code in BPSI**
    - Modular structure, Unified Standard data interface
  - **Various Heating and Current Drive Scheme**
    - Full wave analysis for IC and AW
    - Ray and beam tracing for EC and LH
    - 3D Fokker-Planck analysis
  - **High Portability**
  - **Development using CVS**
  - **Open Source**
  - **Parallel Processing using MPI Library**
  - **Extension to Toroidal Helical Plasmas**

Modules of TASK

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

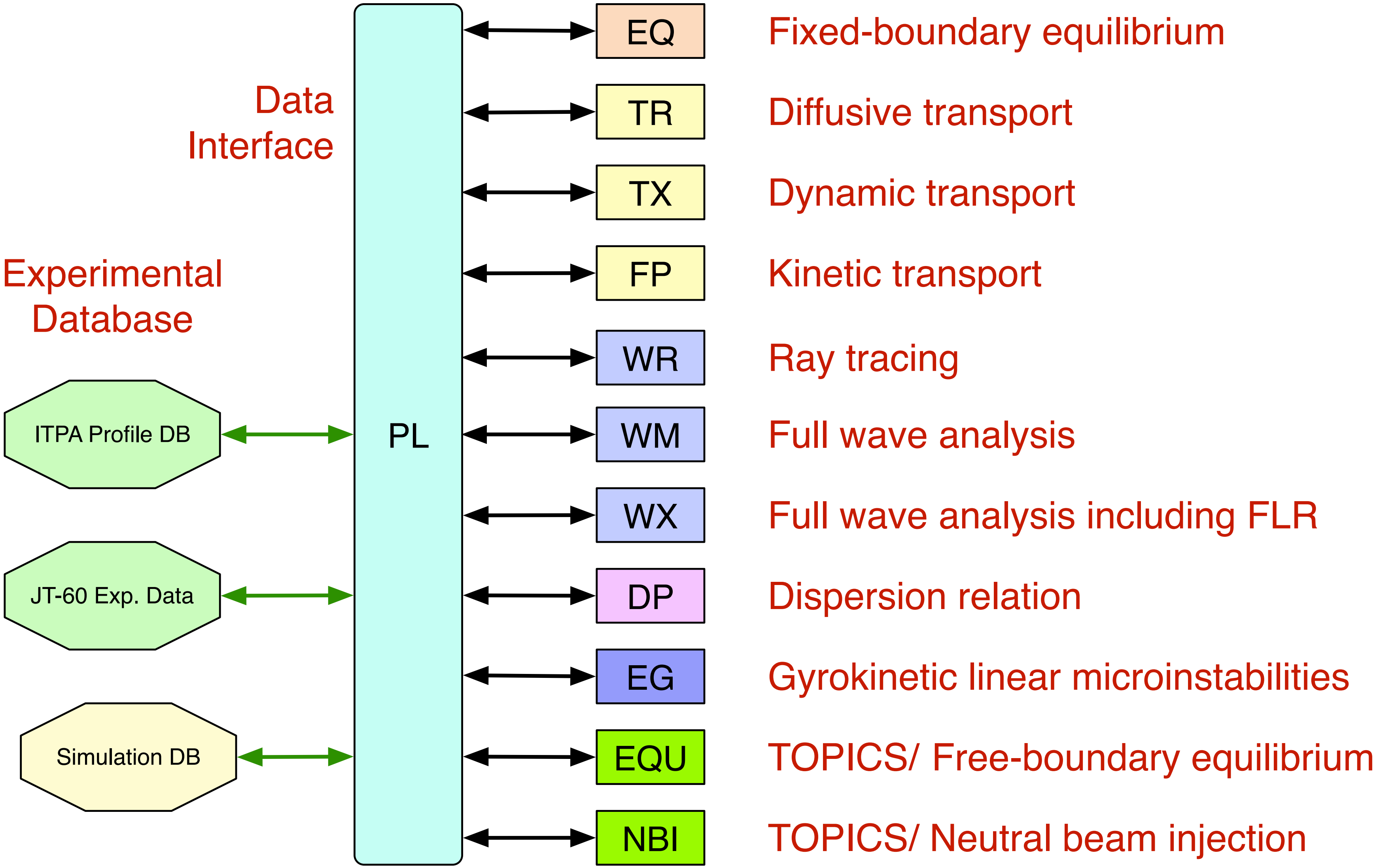
Under Development

TX	Transport analysis including plasma rotation and E_r
EG	Gyrokinetic linear stability analysis

Imported from TOPICS

EQU	Free boundary equilibrium
NBI	NBI heating

Modular Structure of TASK



EQ Fixed-boundary equilibrium

TR Diffusive transport

TX Dynamic transport

FP Kinetic transport

WR Ray tracing

WM Full wave analysis

WX Full wave analysis including FLR

DP Dispersion relation

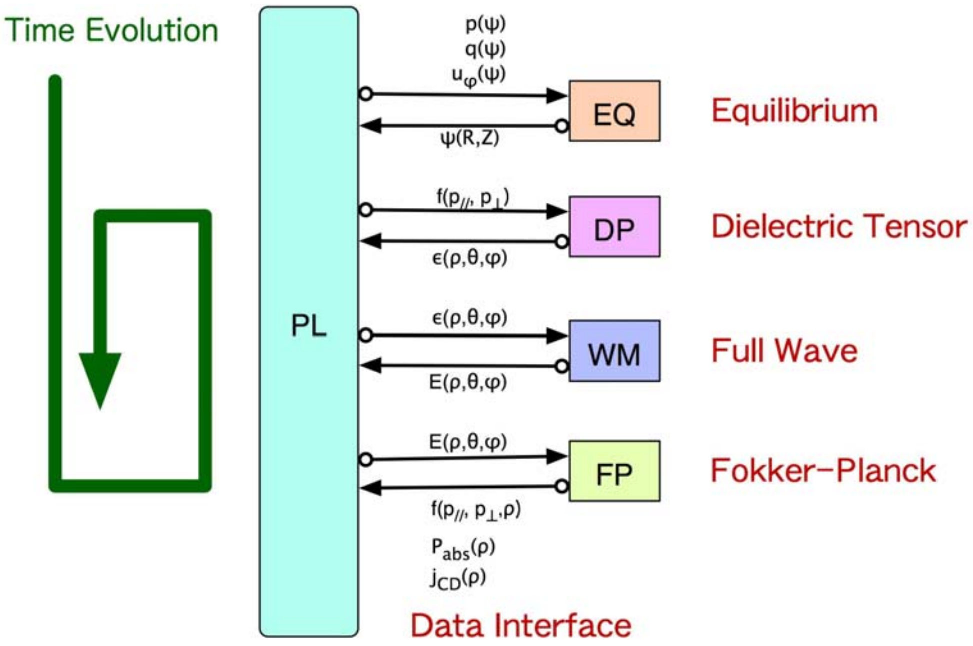
EG Gyrokinetic linear microinstabilities

EQU TOPICS/ Free-boundary equilibrium

NBI TOPICS/ Neutral beam injection

Self-Consistent Wave Analysis with Modified $f(v)$

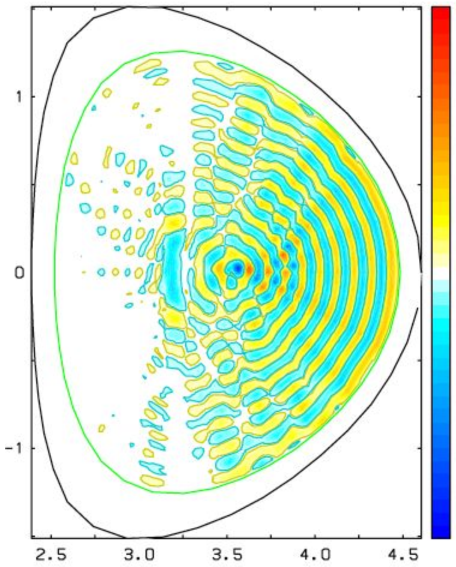
- **Modification of velocity distribution from Maxwellian**
  - Energetic ions generated by ICRF waves
  - Alpha particles generated by fusion reaction
  - Fast ions generated by NB injection
- **Self-consistent wave analysis including modification of $f(v)$**



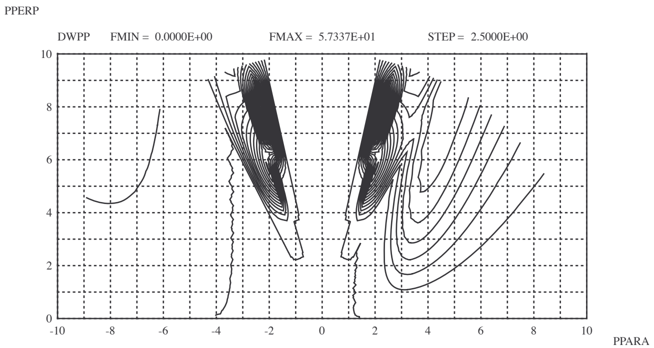
Preliminary Results

- **Tail formation by ICRF minority heating**

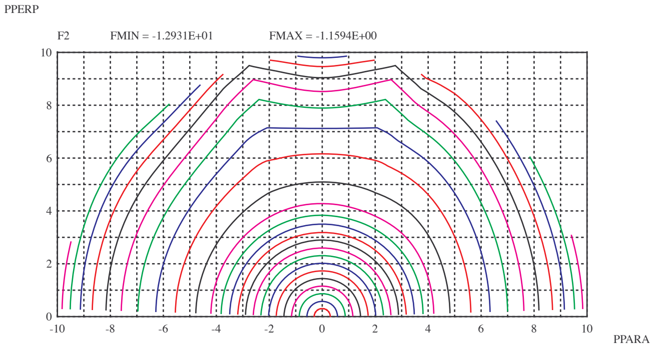
Wave pattern



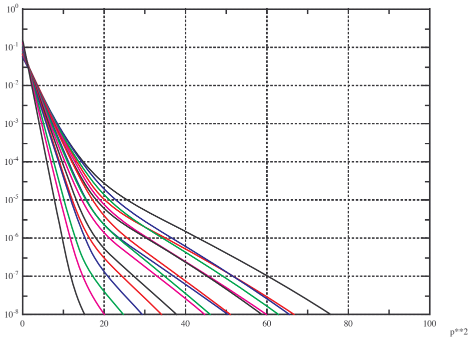
Quasi-linear Diffusion



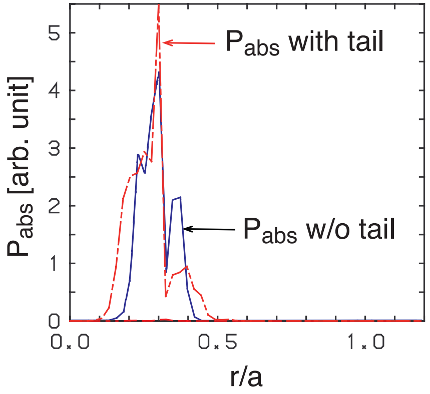
Momentum Distribution



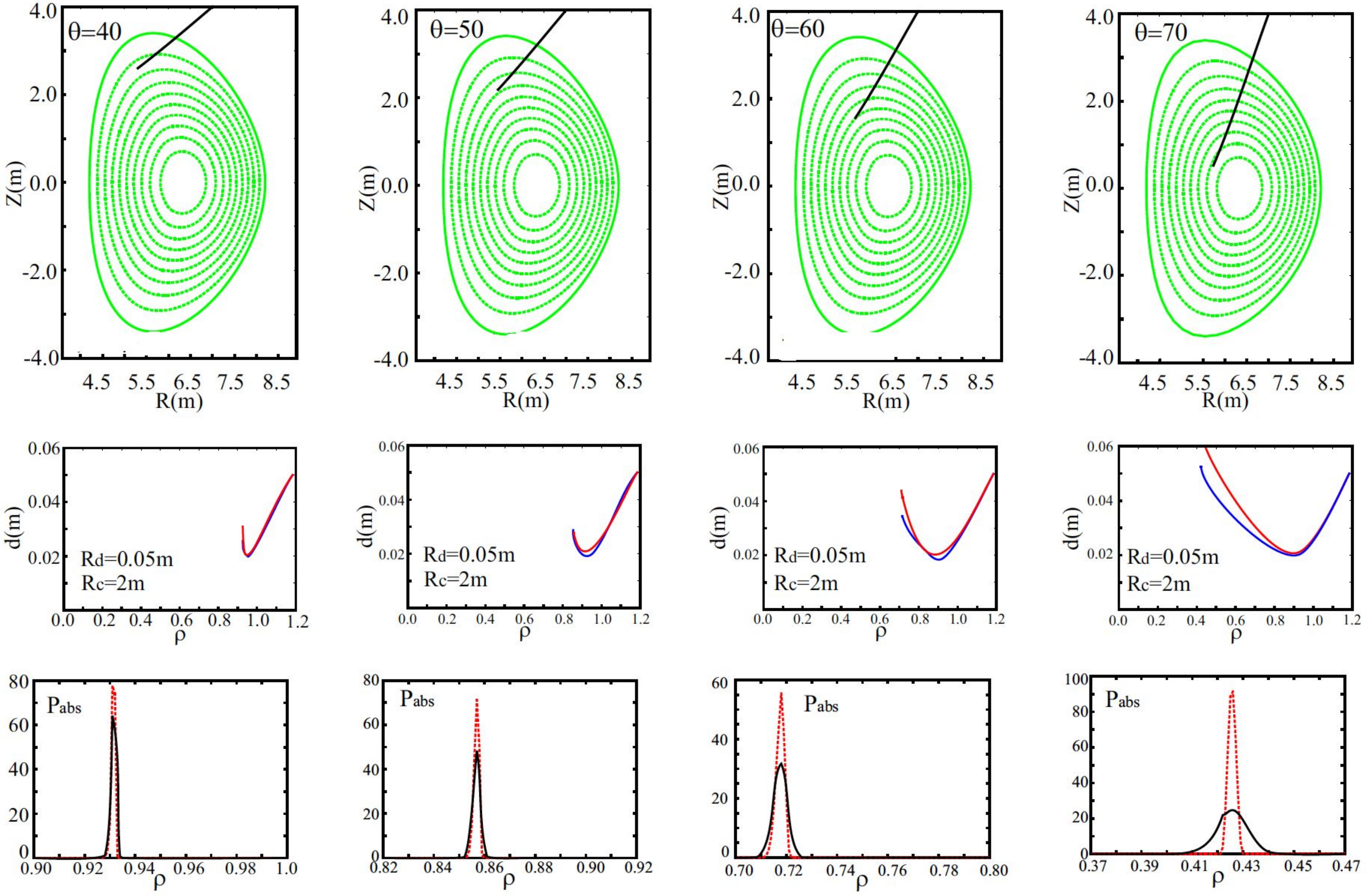
Tail Formation



Power deposition



Beam Tracing Analysis of ECCD



Coupled with 3D Fokker-Planck code TASK/FP

CDBM Transport Model: CDBM05

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

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

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

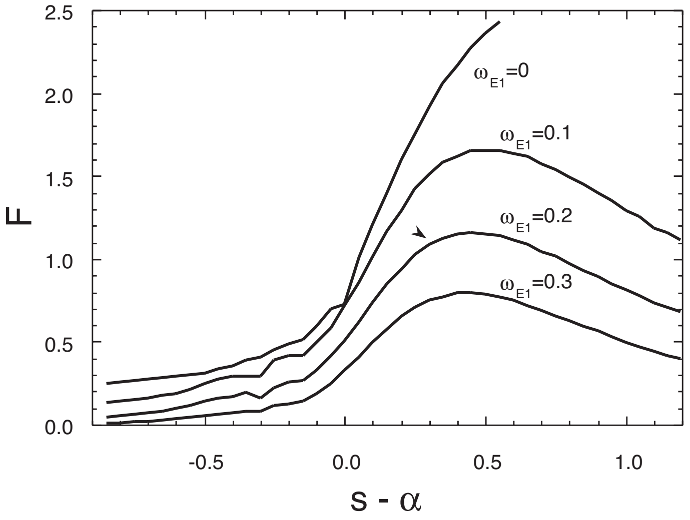
Pressure gradient $\alpha \equiv -q^2 R \dfrac{\mathrm{d}\beta}{\mathrm{d}r}$

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



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

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

The Way of Simulation

- **Neoclassical Transport Models**: **NCLASS**[6]
- **Turbulent Transport Models**: **CDBM, GLF23 v1.61 (retuned)**[6]**, Weiland**
  - CDBM: No $\boldsymbol{E} \times \boldsymbol{B}$ shearing (ω_{E1}) and magnetic curvature (κ_*) effects
  - GLF23: Using toroidal rotation velocity (V_{tor}) from exp. data
  - Weiland: Assuming $k_\theta \rho_s = 0.316$
- **Solve thermal transport equations**
  - **Fixed density profiles**
  - Taken from experimental analysis data in **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}, j, Q_{heating}, $S_{\mathrm{NB,wall}}$, V_{rot}, Metrics
    - — $T_{\mathrm{e,i}}$ data used only for initial profiles and boundary conditions
    - — q data used only if j is not available.
  - **Boundary conditions** enforced at $\rho \leq 0.9$
  - **Particle flux calculated from $S_{\mathrm{NB,wall}}$ in thermal equations**
  - Diagonal turbulent transport coefficient set to zero if negative

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[6] By courtesy of NTCC site (http://w3.pppl.gov/ntcc/)

Conditions for Comparison

- Comparison of resulting $T_{\mathrm{e,i}}$ profiles with experimental data in each discharge
  - At a fully relaxed time (typically $0.5\ \mathrm{s}$)
  - Compared with fitted temperature profiles, not measured ones
- **55 discharges described** in **"ITER Physics Basis: Chapter 2[7]"**
  - 38 L-mode discharges
  - 14 H-mode discharges with small ELMs
  - 3 H-mode discharges with giant ELMs
- **Figures of merit**
  - **Relative RMS error, $\sigma_{\mathrm{T}}^{\mathrm{rel}}$, relative to the maximum experimental temperature for each temperature profile within the region of $0.2 \le \rho \le 0.9$**

$$\sigma_{\mathrm{T}}^{\mathrm{rel}} = \sqrt{\frac{1}{N}\sum_{j=1}^{N}\epsilon_j^2}, \quad \epsilon_j = \frac{T_j^{\mathrm{sim}} - T_j^{\mathrm{exp}}}{T_{\mathrm{max}}^{\mathrm{exp}}}$$

T_j: jth point of experimental data and simulation result for each temperature
N: the number of experimental data points in a profile

  - **Six figures of merit defined in ITER Physics Basis as described later**

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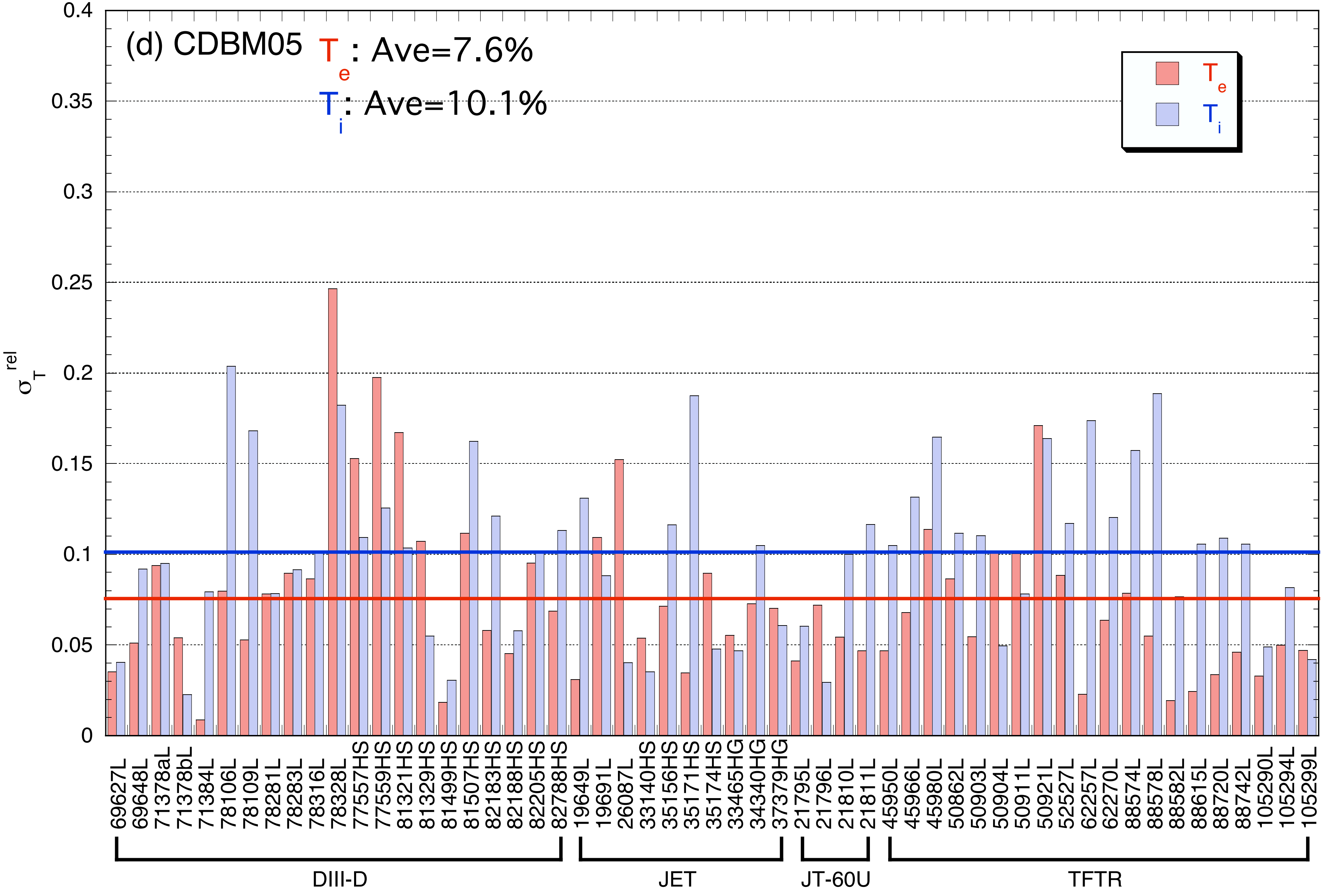
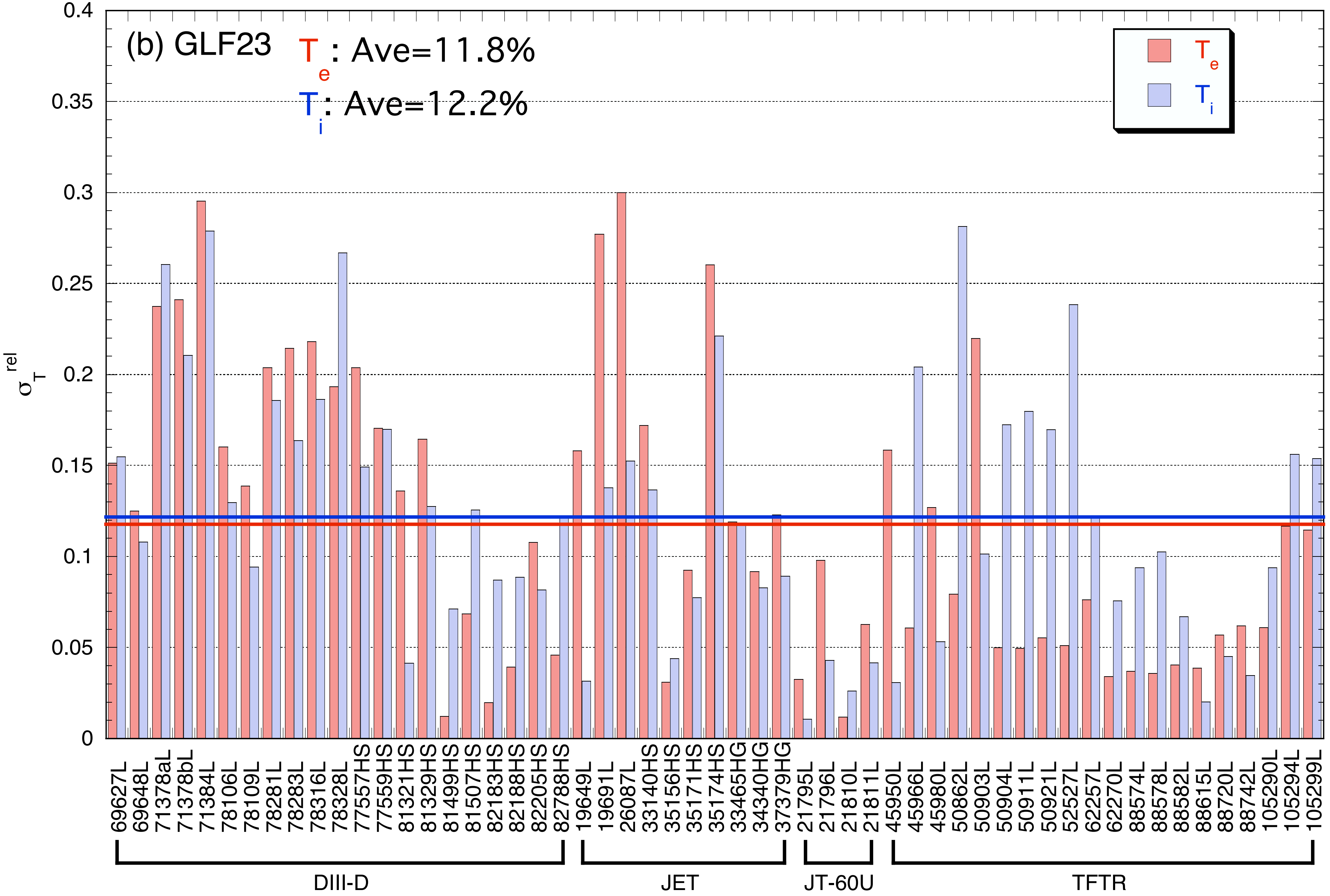
[7] ITER Physics Basis Expert Groups 1999 *Nucl. Fusion* **39** 2175-2249

Relative RMS Error for Temperature Profiles (CDBM05)

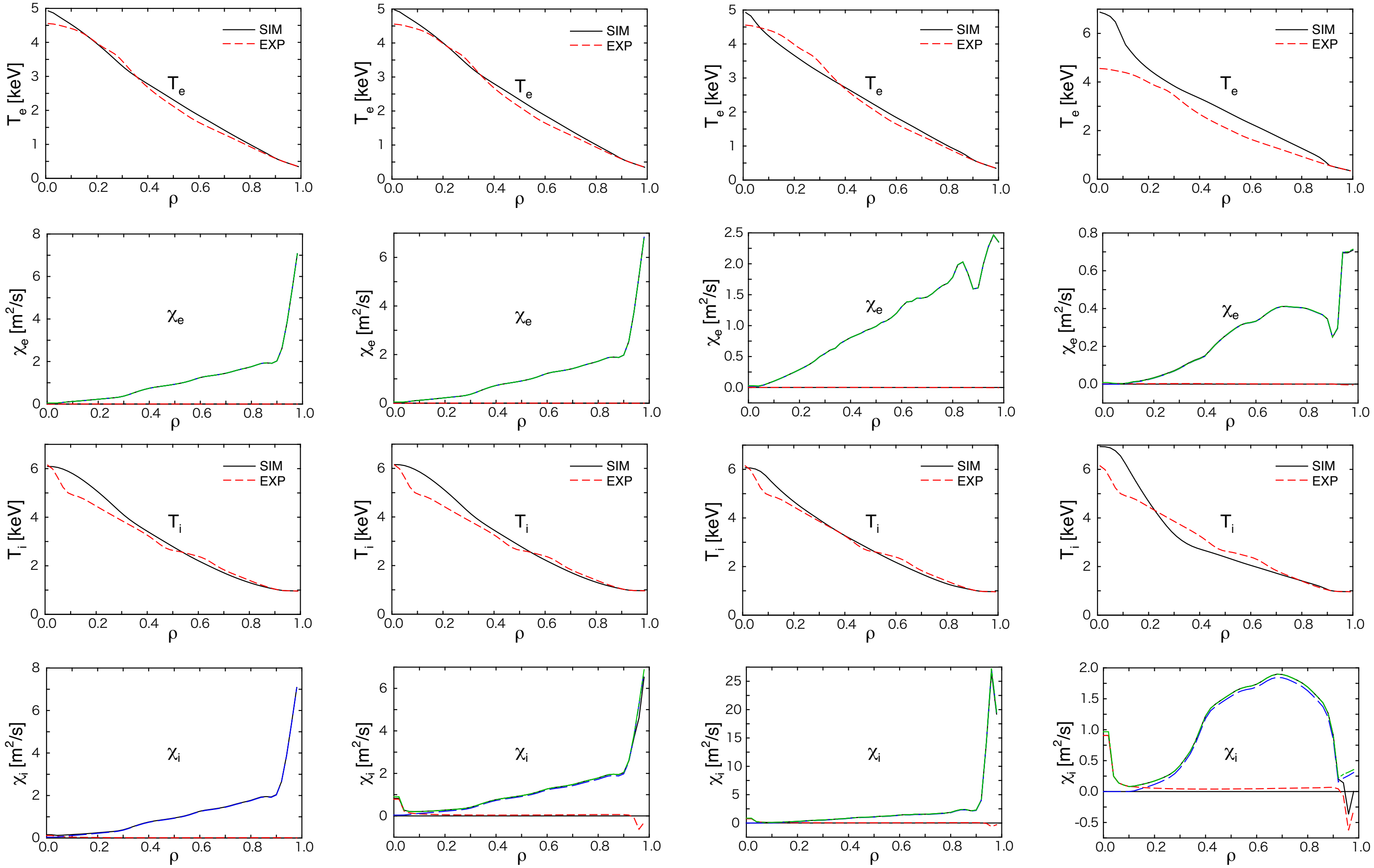


Relative RMS Error for Temperature Profiles (GLF23)

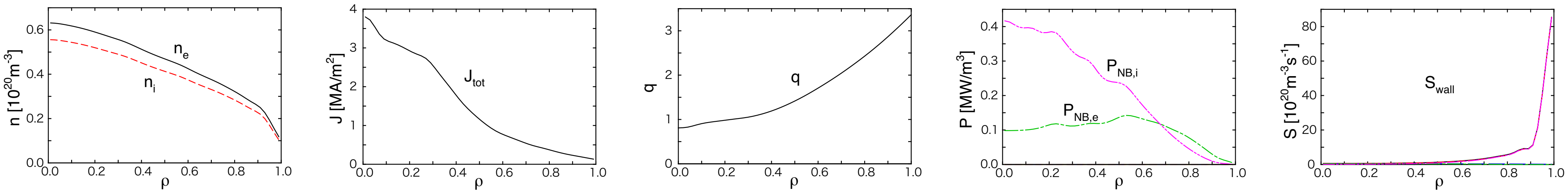


TFTR #88615 (L-mode, NBI heating)

CDBM **CDBM05** **GLF23** **Weiland**

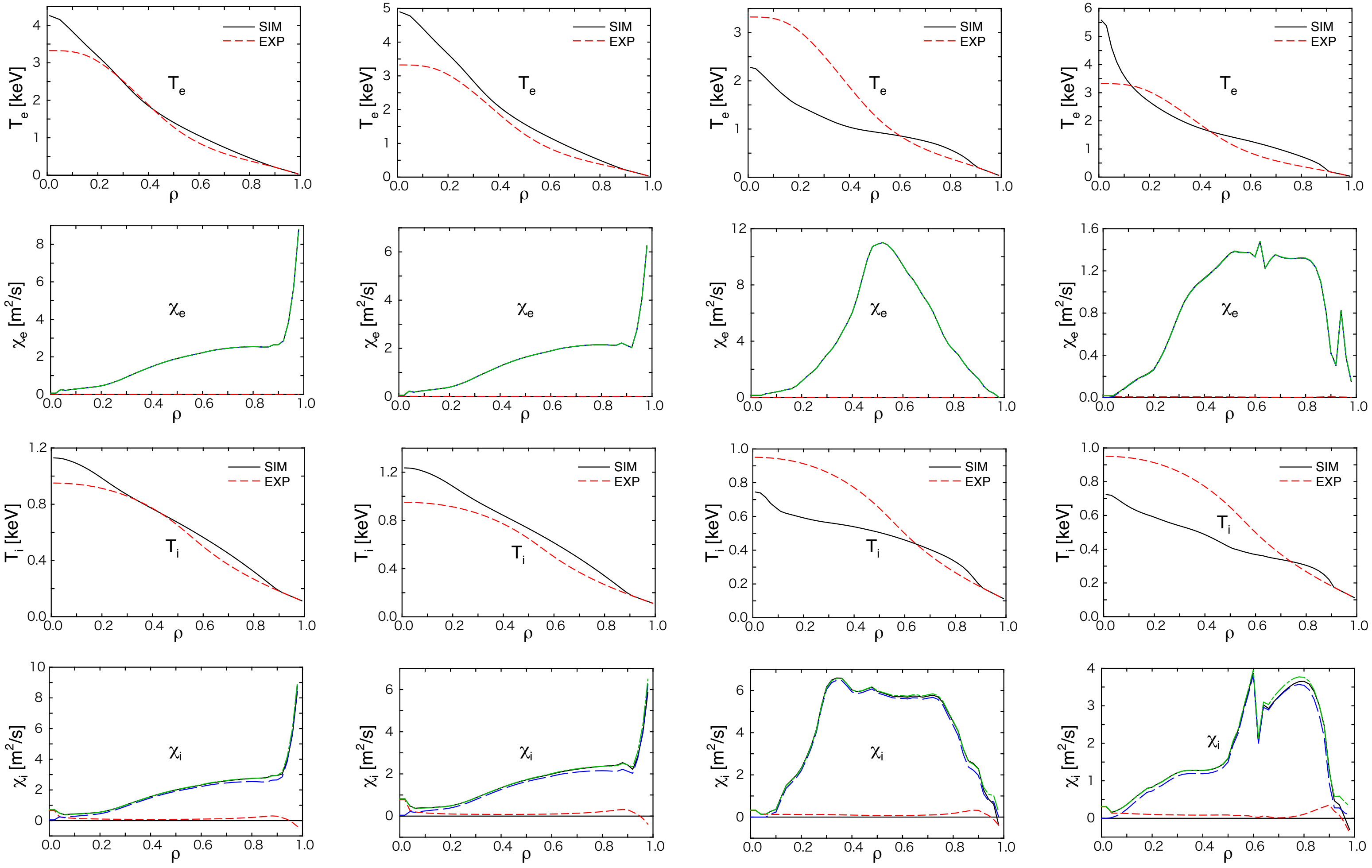


Common Profiles

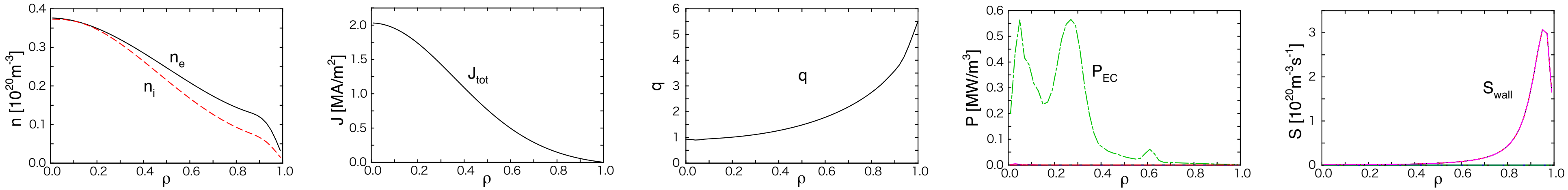


DIII-D #78316 (L-mode, ECH and ICH heatings)

CDBM **CDBM05** **GLF23** **Weiland**



Common Profiles



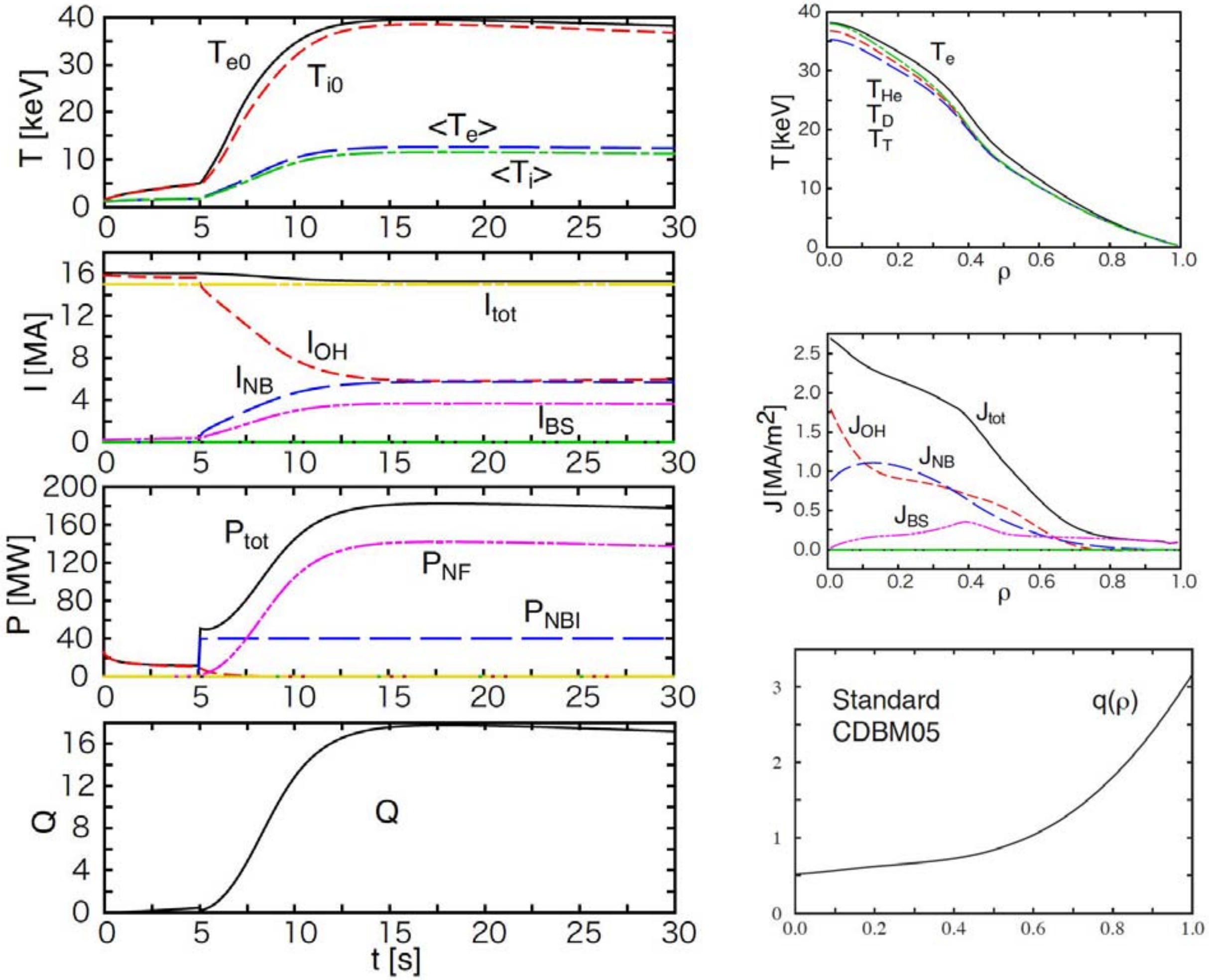
Standard Operation Scenario

- Large plasma current: $I_{\rm p} = 15\,{\rm MA}$, On-axis heating: $P_{\rm NB} = 40\,{\rm MW}$
- Positive shear profile, Small $f_{\rm BS}$

CDBM05

$\beta_{\rm N} = 2.63$

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



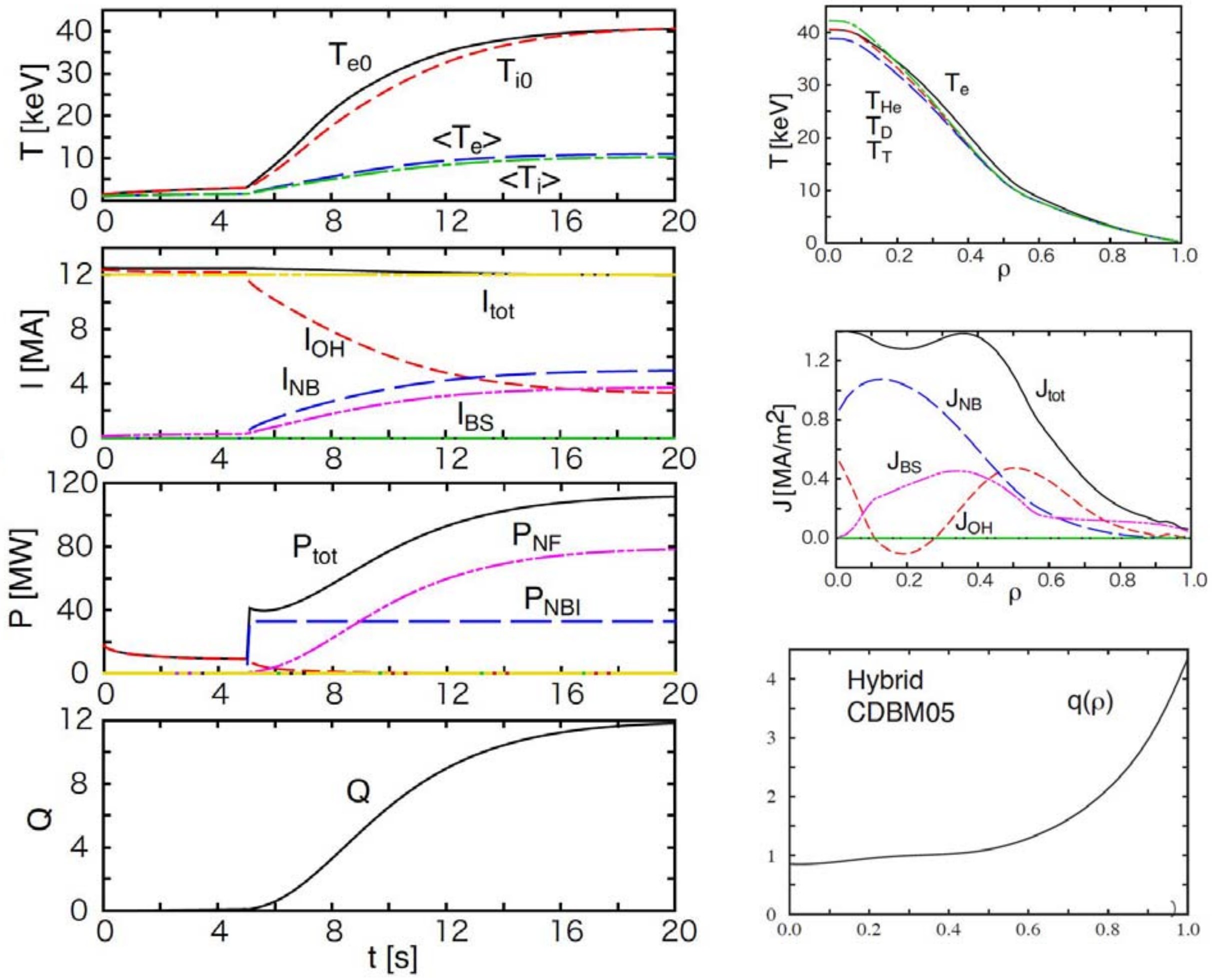
Hybrid Operation Scenario

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

CDBM05

$\beta_\mathrm{N} = 2.58$

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



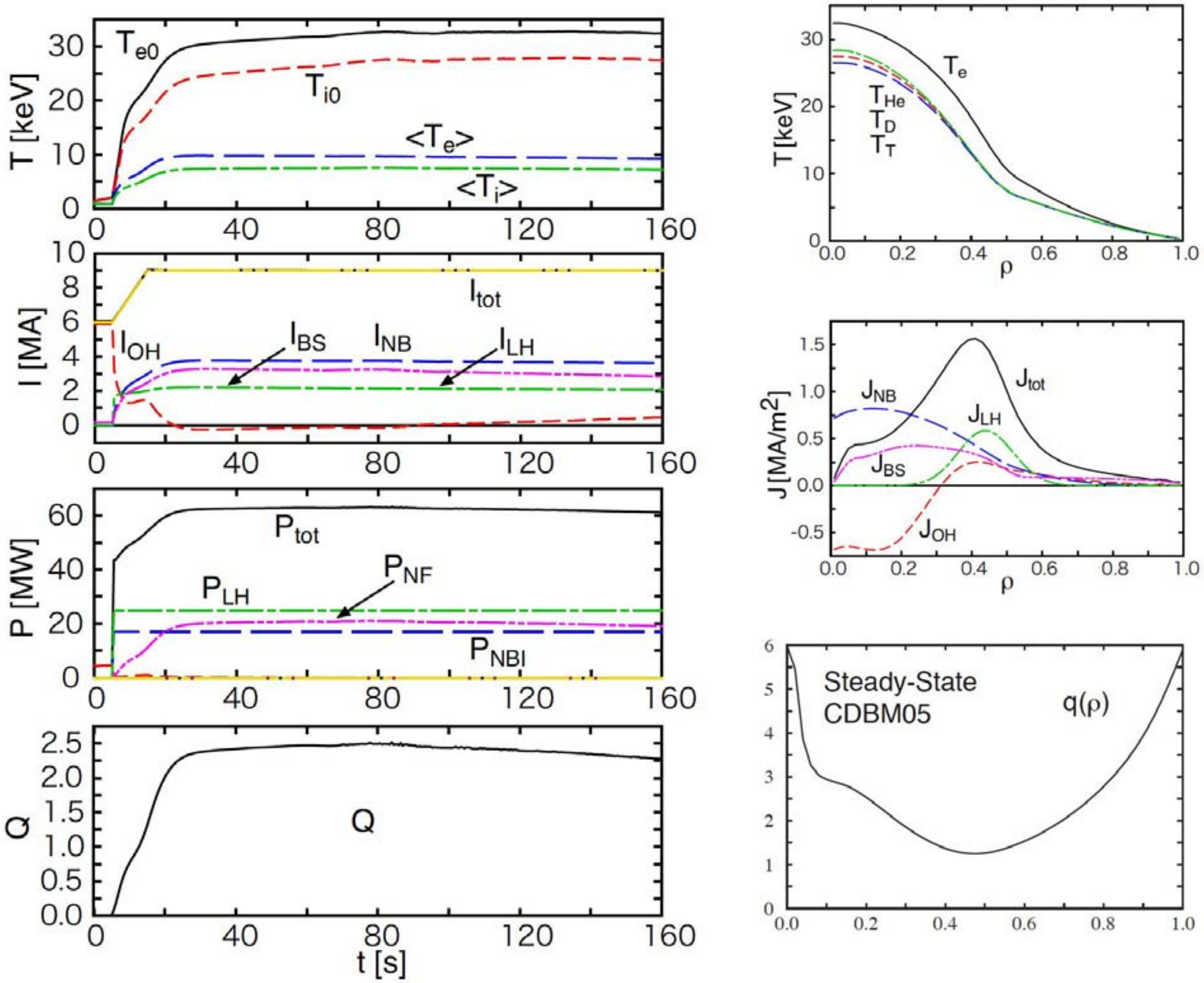
Quasi-Steady State Operation Scenario

- Current ramp up: $I_\mathrm{p} = 6 \rightarrow 8\,\mathrm{MA}$, $P_\mathrm{NB} = 17\,\mathrm{MW}$, $P_\mathrm{LH} = 25\,\mathrm{MW}$
- Reversed shear profile, $I_\mathrm{OH} \sim 0$

CDBM05

$\beta_\mathrm{N} = 1.55$

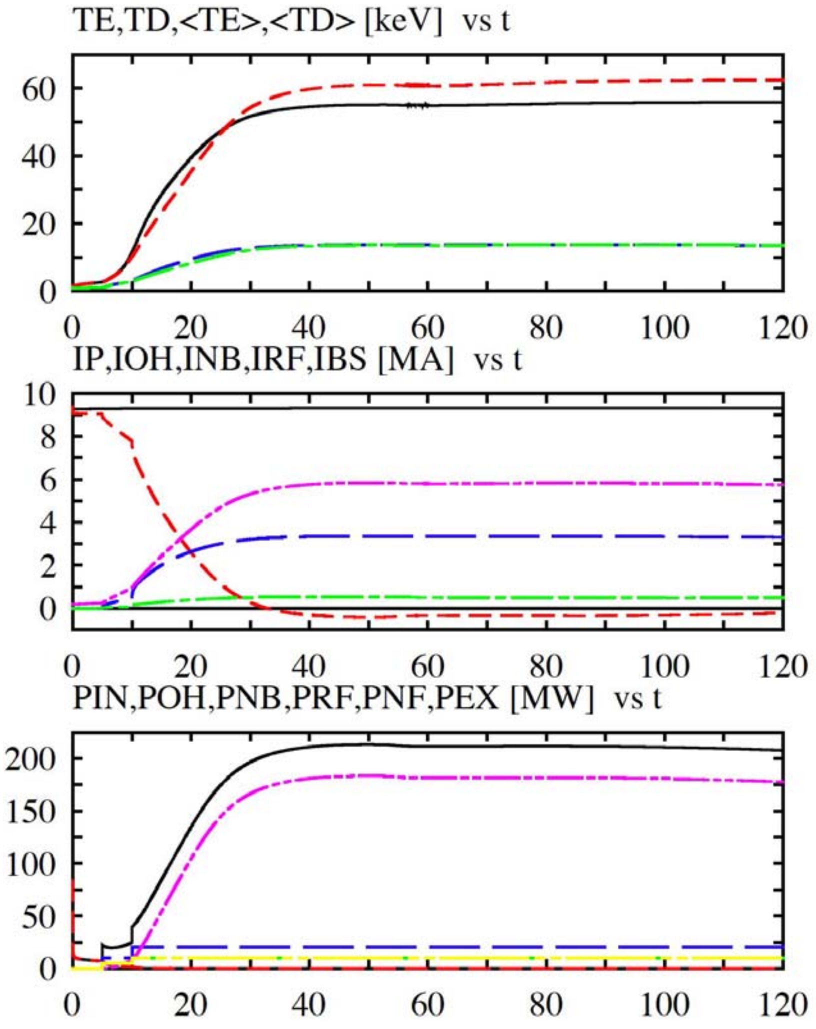
$\tau_\mathrm{E} = 3.2\ \mathrm{s}$

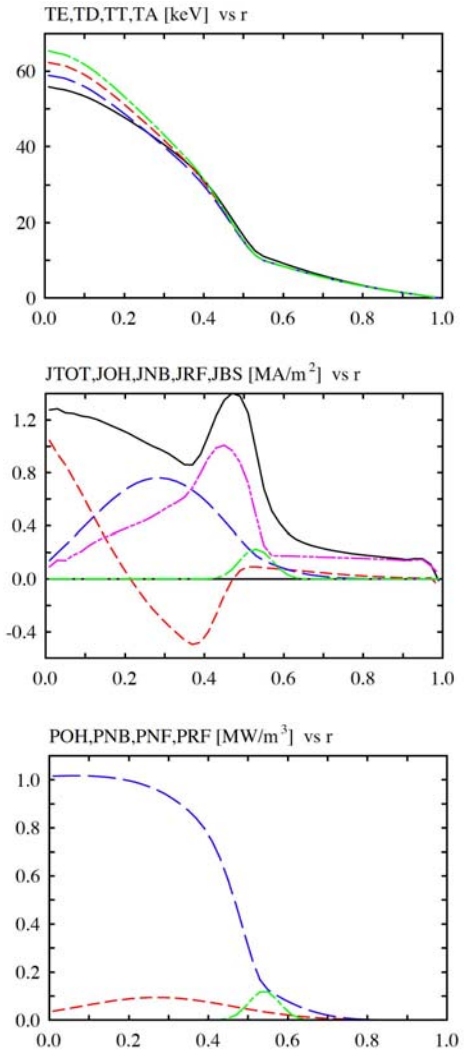


ITER Steady-State Operation (1)

- Off-axis NBI: $20\,\mathrm{MW}$ at $r = 0.5\,\mathrm{m}$
- Off-axis ECCD: $10\,\mathrm{MW}$ at $r = 1.0\,\mathrm{m}$

sustained.



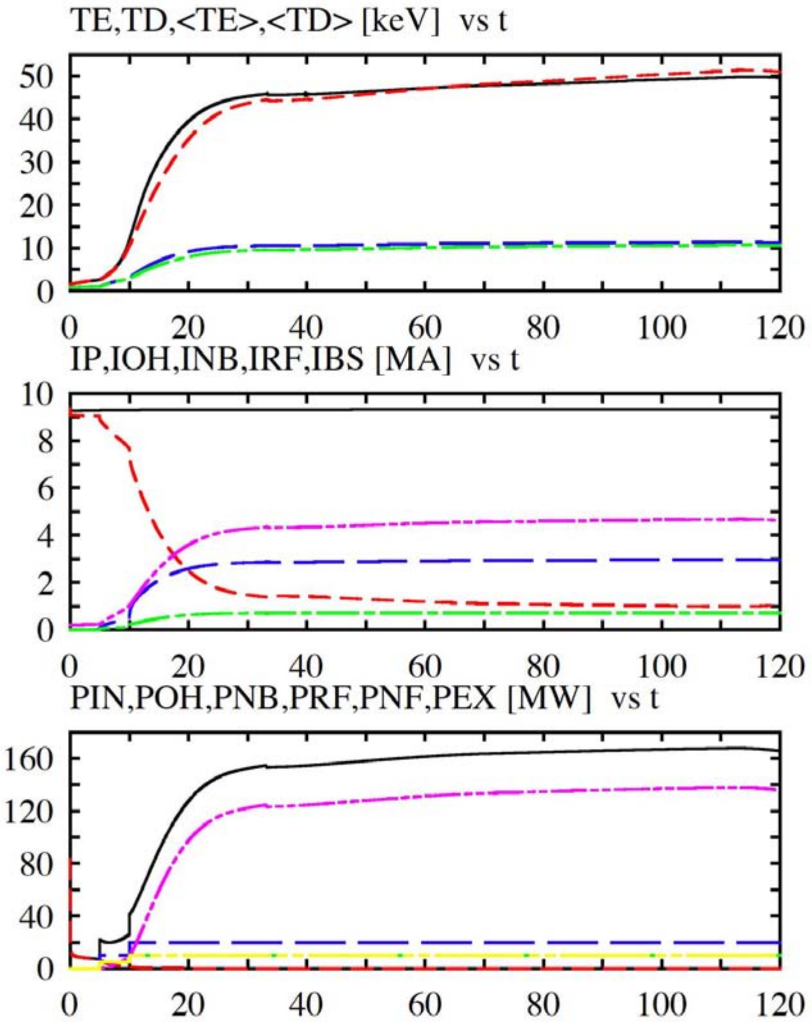


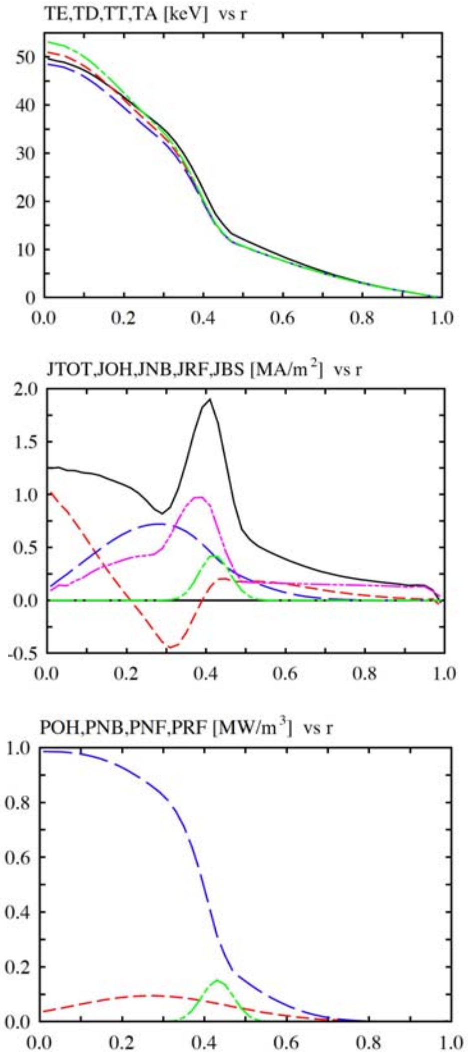
ITER Steady-State Operation (2)

- Off-axis NBI: $20\,\mathrm{MW}$ at $r = 0.5\,\mathrm{m}$

not enough power.

- Off-axis ECCD: $10\,\mathrm{MW}$ at $r = 0.8\,\mathrm{m}$

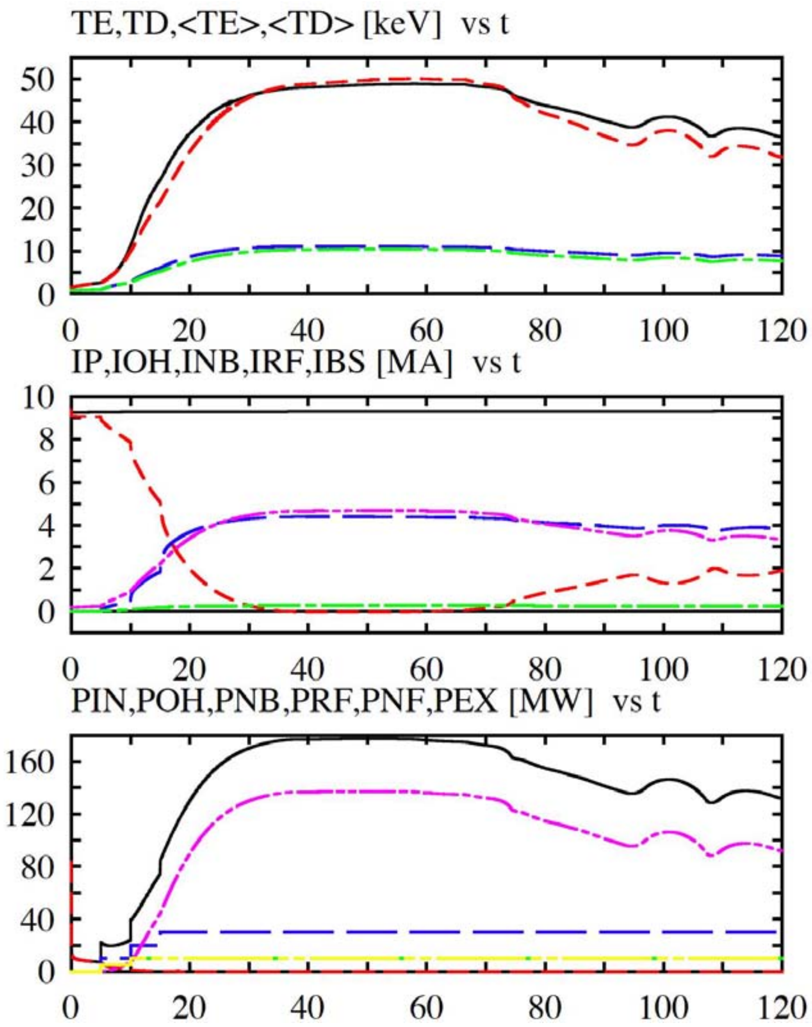


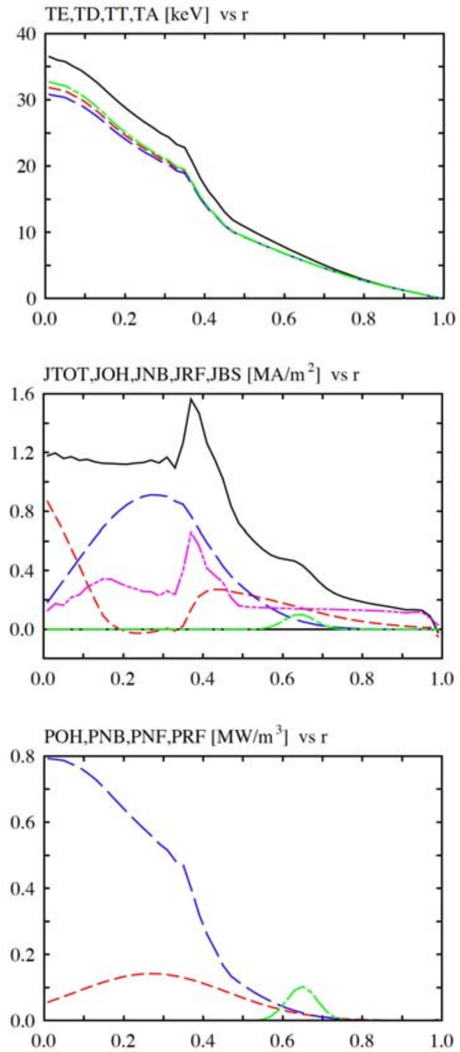


ITER Steady-State Operation (3)

- Off-axis NBI: $30\,\mathrm{MW}$ at $r = 0.5\,\mathrm{m}$
- Off-axis ECCD: $10\,\mathrm{MW}$ at $r = 1.2\,\mathrm{m}$

cannot be sustained.



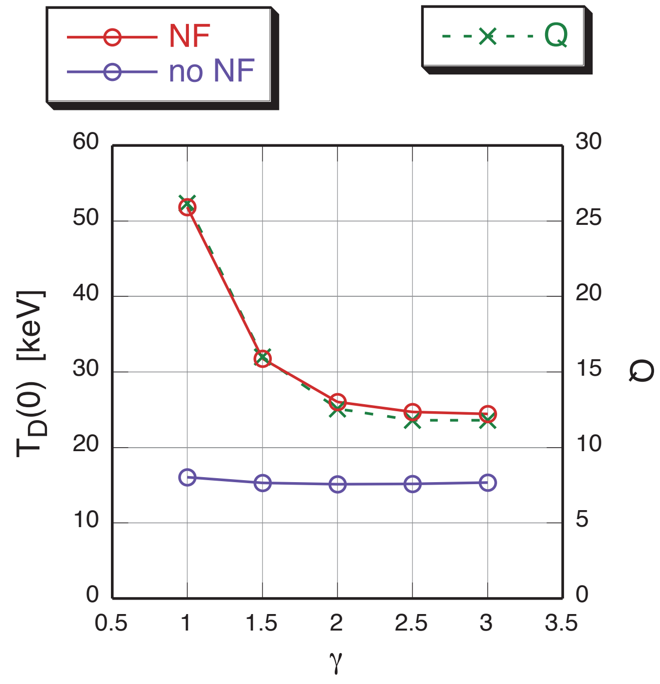


Dependence on Initial Current Profile

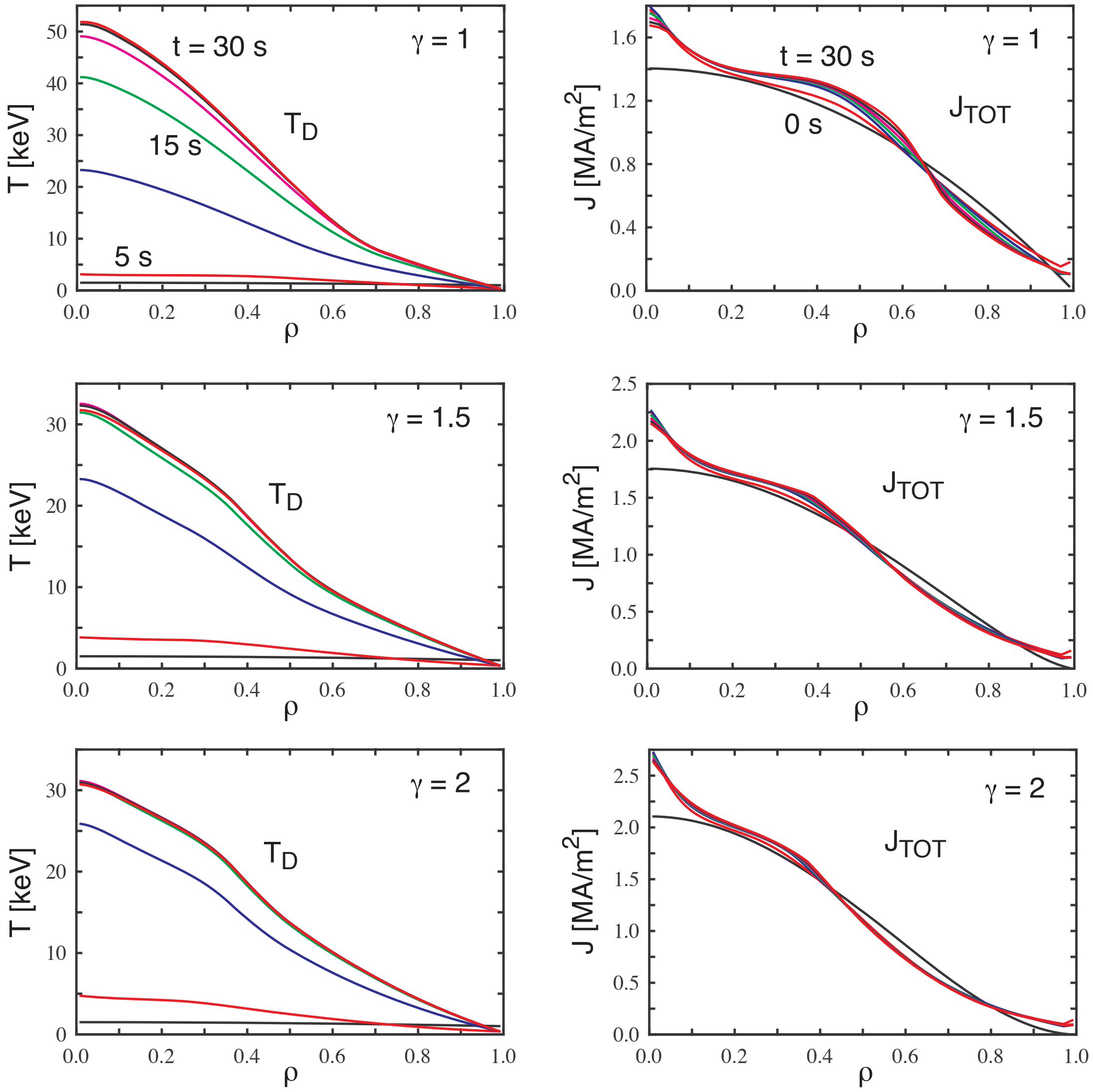
- **Initial current profile**

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

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



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



Summary

- We are developing **the TASK code** for integrated modeling of burning plasmas including ITER. Self-consistent analysis is necessary for especially burning plasmas.

- 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.

- The sustatinment of steady-state is **sensitive to the ECCD location**. Systematic survey of various parameters will improve the understanding of the physical mechanisms.

- **Work in progress**
  - More consistent simulation of ITER plasma
    - Particle transport coupled with plasma rotation
    - Wave heating and current drive including $f(\boldsymbol{v})$ modification
    - FLR effects in full wave analysis