Workshop on Transport and Confinement
NIFS University, 2006/11/09

Integrated Transport Simulation Aiming at Burning Plasmas

A. Fukuyama and M. Honda
Department of Nuclear Engineering, Kyoto University

Contents

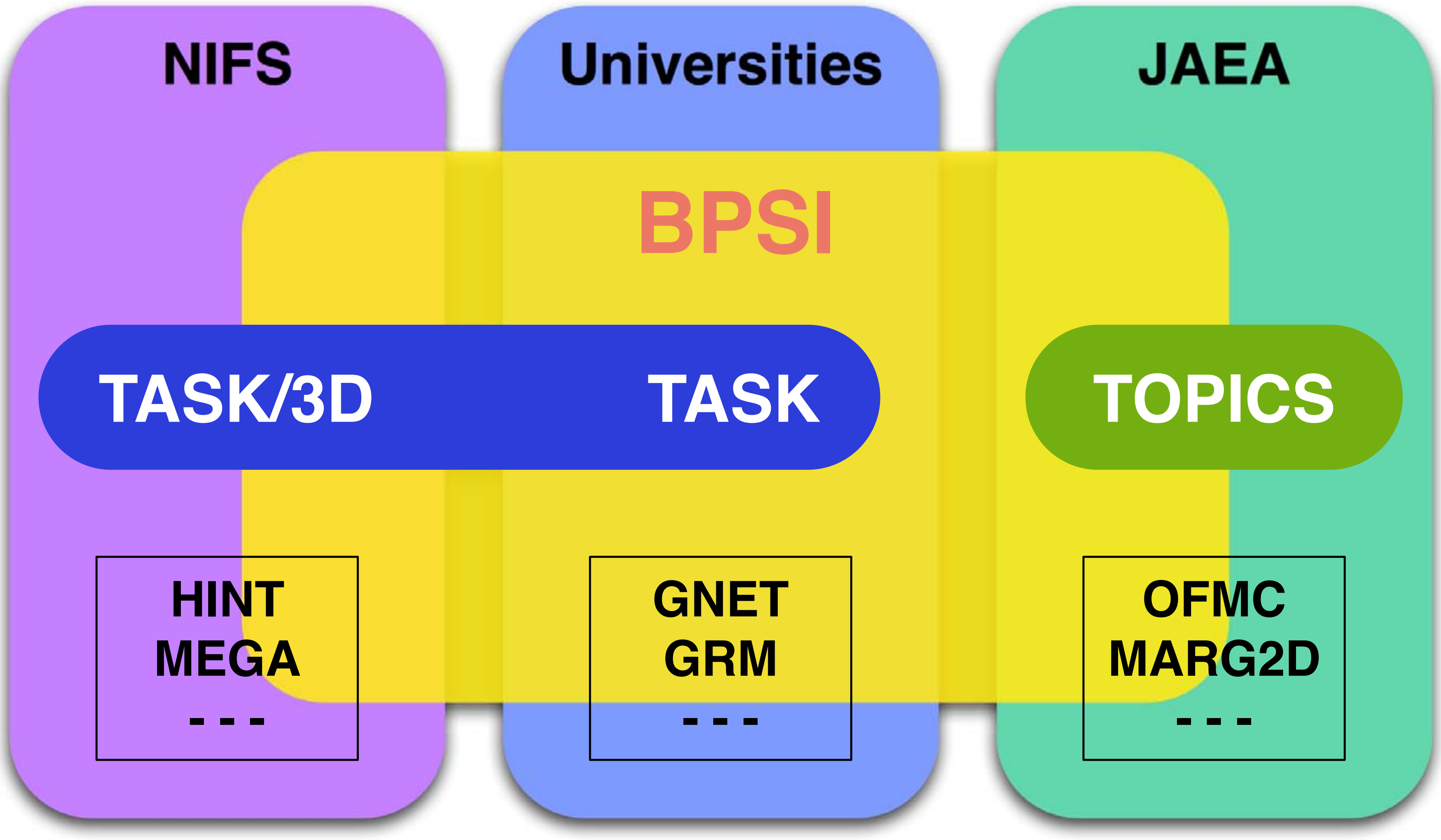
- Status of BPSI ans TASK
- Status of Burning Plasma Simulation (Kessel, IAEA)
- Advanced transport simulation: TASK/TX (Honda)
- Summary

Burning Plasma Simulation

- **Simulation describing a burning plasma:**
  - **Whole plasma** (core & edge & diverter & wall-plasma)
  - **Whole discharge**
    (startup & sustainment & transients events & termination)
  - **Reasonable accuracy** (validation with experimental data)
  - **Reasonable computer resources** (still limited)
- **Target of BPSI**
  - **Framework** for collaboration of various plasma simulation codes
  - **Physics integration** with different time and space scales
  - **Advanced technique** of computer science

Integrated Code Development Based on BPSI Framework

Integrated code: TASK and TOPICS



TASK Code

- **Features**
  - **Core of Integrated Modeling Code in BPSI**
    - Modular structure
    - Reference data interface and standard data set
  - **Various Heating and Current Drive Scheme**
    - EC, LH, IC, AW, NB
  - **High Portability**
  - **Development using CVS** (Concurrent Version System)
  - **Open Source** (V1.0: Fortran95, **http://bpsi.nucleng.kyoto-u.ac.jp/task/**)
  - **Parallel Processing using MPI Library**
  - **Extension to Toroidal Helical Plasmas**

Modules of TASK

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, 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
LIB	**Libraries**	LIB, MTX, MPI

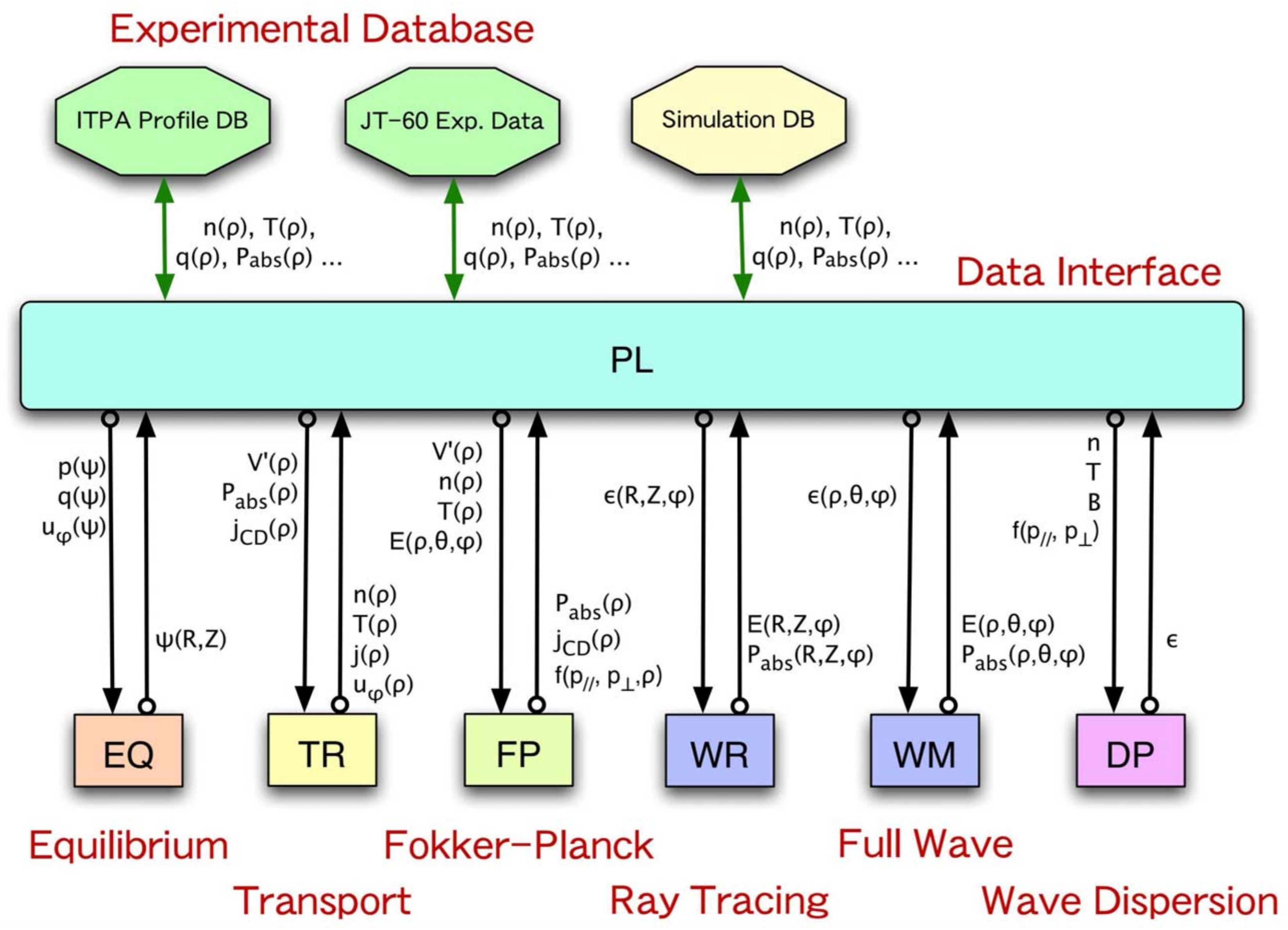
Under Development

TX	Transport analysis including plasma rotation and E_r

Collaboration with TOPICS

EQU	Free boundary equilibrium
NBI	NBI heating

Modular Structure of TASK

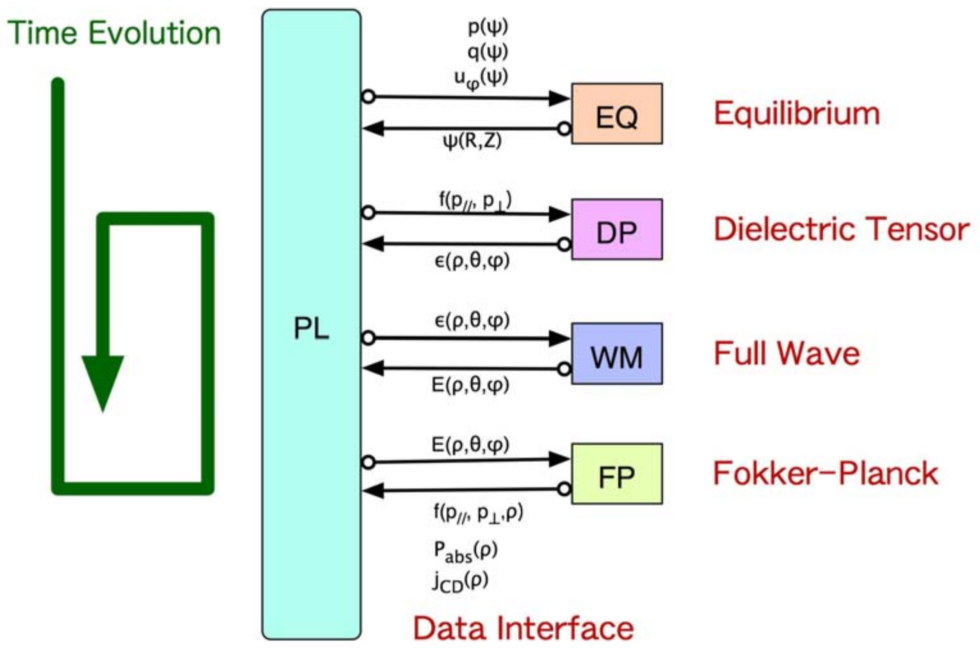


Recent progress in TASK code

WM/FP/DP	Development of Self-Consistent Wave Analysis
EQ/TR	Transport Simulation for ITER
	Benchmark test for ITER Hybrid/SS scenario (Kessel)
TX	Dynamical Transport Simulation including Rotation
EQU/NBI	Common Module Interface
3D	Collaboration with NIFS

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

- **Modification of velocity distribution from Maxwellian**
  - Absorption of ICRF waves in the presence of energetic ions
  - Current drive efficiency of LHCD
  - NTM controllability of ECCD (absorption width)
- **Self-consistent wave analysis including modification of $f(v)$**

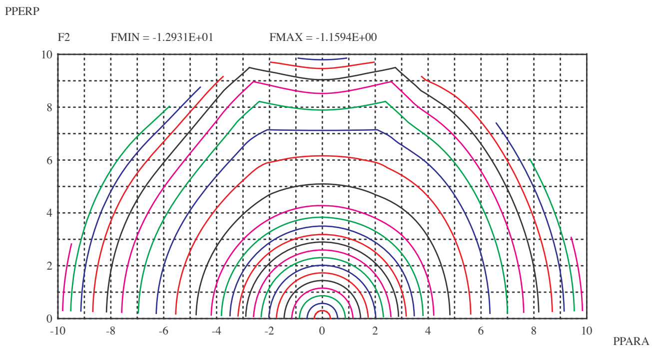


Development of Self-Consistent Wave Analysis

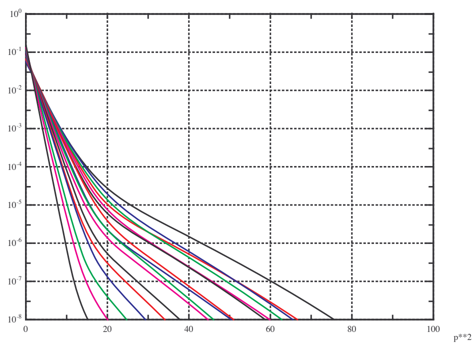
- **Code Development in TASK**
  - Ray tracing analysis with arbitrary $f(v)$: **Already done**
  - Full wave analysis with arbitrary $f(v)$: **Completed**
  - Fokker-Plank analysis of ray tracing results: **Already done**
  - Fokker-Plank analysis of full wave results: **Almost competed**
  - Self-consistent iterative analysis: **Preliminary**

- **Tail formation by ICRF minority heating**

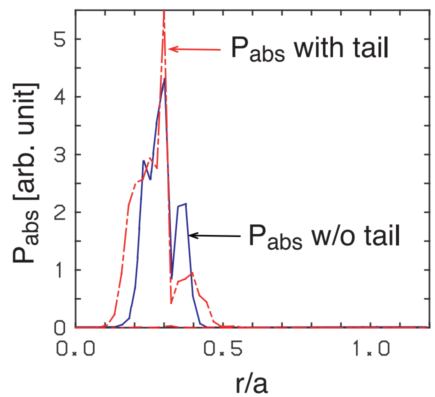
Momentum Distribution



Tail Formation



Power deposition



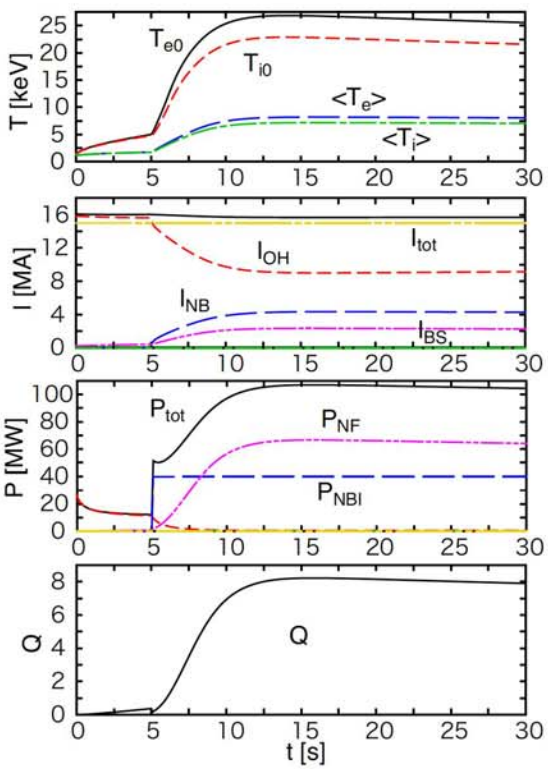
ITER H-mode Scenario

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

CDBM

$\beta_N = 1.49$

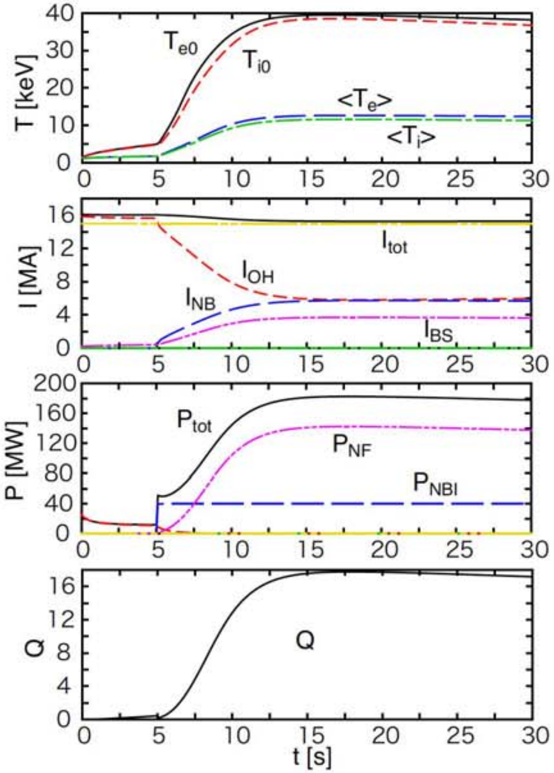
$\tau_E = 3.0$ s

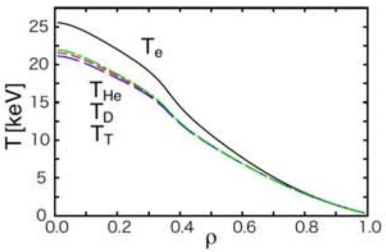


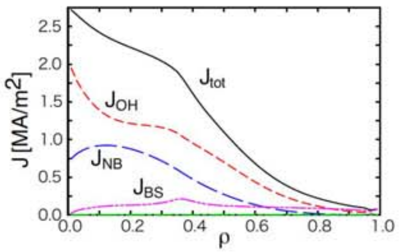
CDBM05

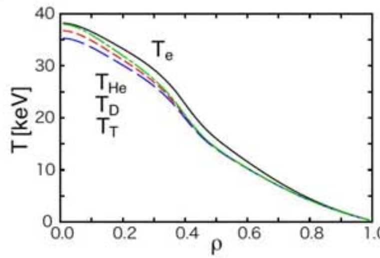
$\beta_N = 2.63$

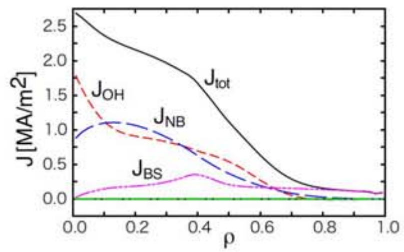
$\tau_E = 3.1$ s





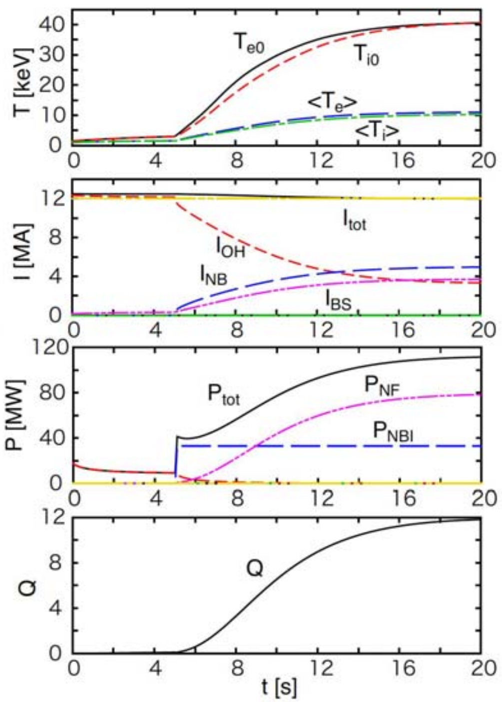




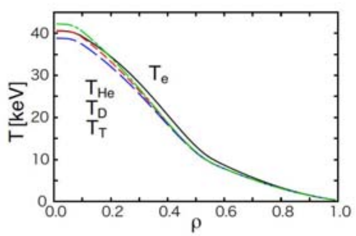


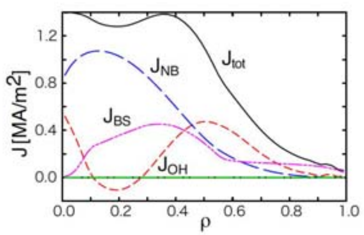
ITER Advanced Scenario

- **Hybrid scenario**
- $I_p = 12\,\mathrm{MA}$, $P_{NB} = 33\,\mathrm{MW}$

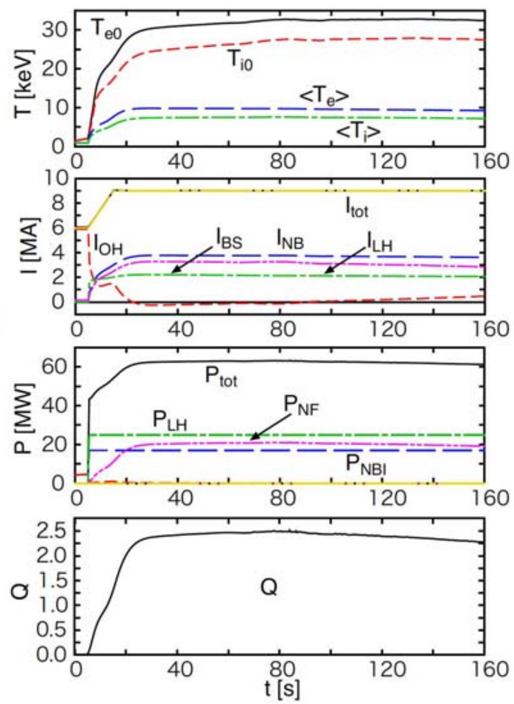


CDBM05
$\beta_N = 2.58$
$\tau_E = 3.6\ \mathrm{s}$

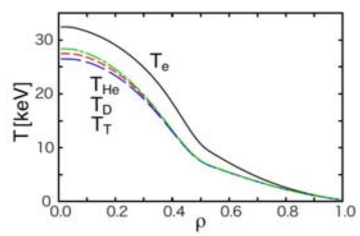




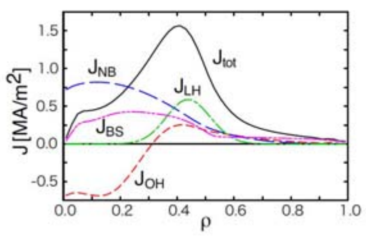
- **Steady state**
- $I_p = 6 \rightarrow 9\,\mathrm{MA}$



CDBM05
$\beta_N = 1.55$
$\tau_E = 3.2\ \mathrm{s}$



$P_{NB} = 17\ \mathrm{MW}$



$P_{LH} = 25\ \mathrm{MW}$

Benchmark Test for ITER Hybrid Scenario

- **C.E. Kessel et al.: IAEA2006 IT/P1-7** (ITPA/SSO)
- Codes: **CRONOS, ONETWO, TSC/TRANSP, TOPICS, ASTRA**

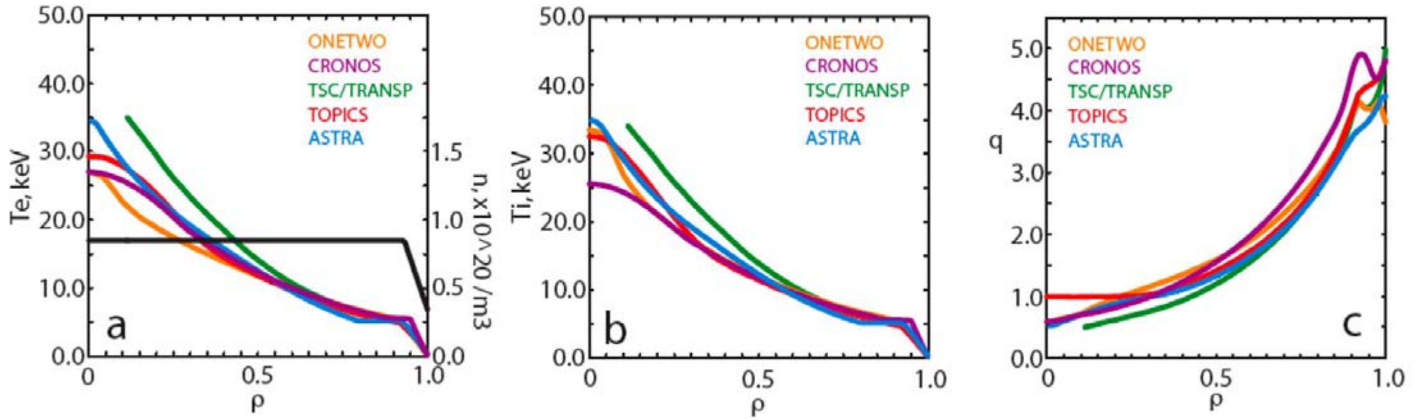


Figure 1. Electron temperature profiles and density profile (a), ion temperature profiles (b), safety factor profiles (c), for the NB+IC ITER Hybrid simulations.

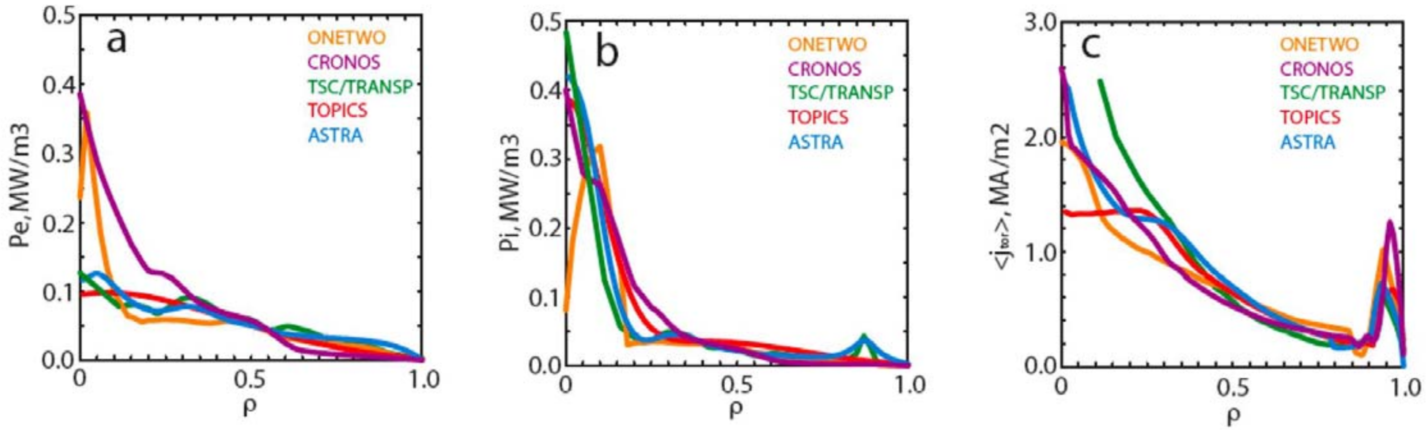


Figure 2. External power deposition profiles to electrons (a) and ions (b) and the toroidal current density (c) for the NB+IC ITER Hybrid simulations.

Benchmark Test for ITER Steady-State Scenario

- Codes: **TOPICS, CRONOS, TSC/TRANSP**

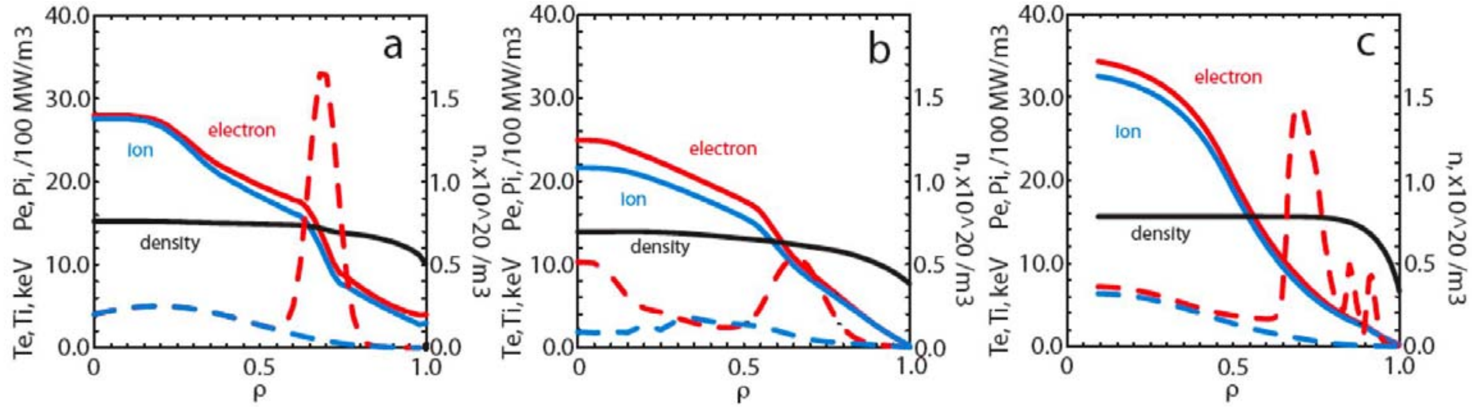


Figure 5. Electron and ion temperature, density, and external power deposition profiles for Steady State ITER simulations, (a) TOPICS (NB+EC), (b) CRONOS (NB+IC+LH), and (c) TSC/TRANSP (NB+IC+LH).

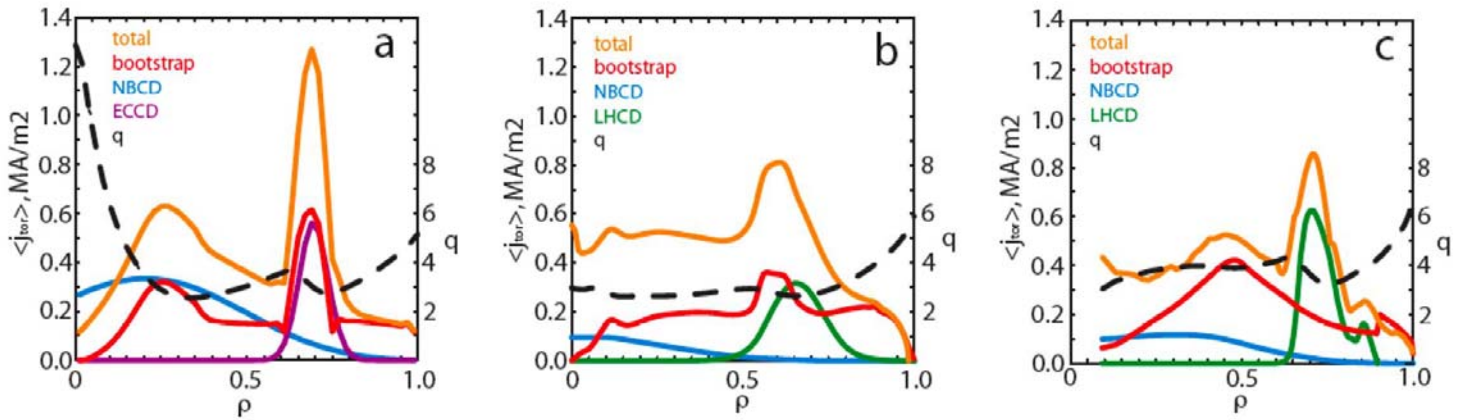


Figure 6. Safety factor and toroidal current density profiles and its contributions for Steady State ITER simulations, (a) TOPICS (NB+EC), (b) CRONOS (NB+IC+LH), and (c) TSC/TRANSP (NB+IC+LH).

Motivation of TASK/TX

- **Transport Simulation including Core and SOL Plasmas**
  - **Role of Separatrix**
    - Closed magnetic surface $\Longleftrightarrow$ Open magnetic field line
    - Difference of dominant transport process
- **Transient Behavior of Plasma Rotation**
  - **Radial Electric Field**: Radial force balance, (Poisson equation)
  - **Poloidal rotation**: Equation of motion
  - **Toroidal rotation**: Equation of motion
  - Equation of motion rather than transport matrix
- **Analysis including Atomic Processes**

1D Transport code: TASK/TX

- **Dynamic Transport Equation**: *Fukuyama et al. PPCF (1994)*
  - **A set of flux-surface averaged equations**
  - **Two fluid equation for electrons and ions**
    - Continuity equation
    - Equation of motion (radial, poloidal, toroidal)
    - Energy transport equation
  - **Neoclassical transport**
    - Poloidal viscosity
  - **Turbulent transport**
    - Ambipolar diffusion through poloidal momentum transfer
    - Thermal diffusivity, Perpendicular viscosity
  - **Maxwell's equation, Poisson's equation**
  - **Slowdown equation for beam component**
  - **Diffusion equation for neutral particles**

Transport Model

- **Neoclassical transport**
  - Poloidal viscosity $\longrightarrow$ radial transport, resistivity, bootstrap current, Ware pinch
    - — **Hirshman and Sigmar**
    - — **NCLASS**
- **Turbulent Diffusion**
  - Perpendicular momentum exchange between electron and ion
  - Non-bipolar flux (electron flux = ion flux)

$$F_{\mathrm{e}\theta}^{\mathrm{W}} = -F_{\mathrm{i}\theta}^{\mathrm{W}} = -\frac{e^2 B_\phi^2 D_\mathrm{e}}{T_\mathrm{e}} n_\mathrm{e} \left(u_{\mathrm{e}\theta} - \frac{B_\theta}{B_\phi} u_{\mathrm{e}\phi} \right),$$

$$F_{\mathrm{e}\phi}^{\mathrm{W}} = -F_{\mathrm{i}\phi}^{\mathrm{W}} = \frac{e^2 B_\phi^2 D_\mathrm{e}}{T_\mathrm{e}} \frac{B_\theta}{B_\phi} n_\mathrm{e} \left(u_{\mathrm{e}\theta} - \frac{B_\theta}{B_\phi} u_{\mathrm{e}\phi} \right),$$

- **Perpendicular viscosity**, **Thermal diffusivity**

Model of Scrape-Off Layer Plasma

- **Particle, momentum and ion heat losses along the field line**
  - Decay time in a sound velocity time scale

$$\nu_\mathrm{L} = \frac{C_\mathrm{s}}{2\pi q R}$$

- **Electron heat loss**
  - Decay time in a thermal diffusion time scale

$$\nu_\mathrm{L} = \frac{\chi_\parallel}{(2\pi q R)^2}$$

- **Recycling from diverter**
  - Recycling rate: $\gamma_0 = 0.8$
  - fixed density and temperature at diverter
- **Gas puff from wall**, **NBI**, **Charge exchange**

Steady State Flux (1)

- **Electron flux**
  - Inertia term in the equation of motion = 0
- **Radial flux**

$$u_{er} = -\frac{1}{1+\alpha}\frac{\bar{\nu}_e + \nu_{ei}}{n_e m_e \Omega_{e\phi}^2}\left[\frac{dP_e}{dr} + \frac{dP_i}{dr}\right] - \frac{\alpha}{1+\alpha}\frac{E_\phi}{B_\theta} + \frac{1}{1+\alpha}\frac{F_\theta^{W}}{n_e m_e \Omega_{e\phi}}$$

$$+ \frac{1}{1+\alpha}\frac{\bar{\nu}_e}{\Omega_{e\phi}}u_{i\theta} + \frac{\alpha}{1+\alpha}\frac{B_\phi}{B_\theta}\frac{\nu_{eb}}{\Omega_{e\phi}}(u_{b\phi} - u_{i\phi})$$

where $\alpha \equiv \dfrac{\bar{\nu}_e + \nu_{ei}}{\nu_{ei} + \nu_{eb}}\dfrac{B_\theta^2}{B_\phi^2}, \quad \nu_{eb} = \dfrac{n_b m_b}{n_e m_e}\nu_{be}$

  - Poloidal neoclassical viscosity $\bar{\nu}_e$
  - Factor α represents parallel neoclassical viscosity
  - First three terms in RHS are neoclassical diffusion, Ware pinch and turbulent diffusion.

Steady State Flux (2)

- **Toroidal current**

$$u_{e\phi} = \frac{-1}{\nu_{ei}+\nu_{eb}} \left\{ \frac{1}{1+\alpha}\frac{e}{m_e}E_\phi + \frac{1}{1+\alpha}\frac{B_\theta}{B_\phi}\frac{\bar{\nu}_e+\nu_{ei}}{n_e m_e \Omega_{e\phi}}\left[\frac{dP_e}{dr}+\frac{dP_i}{dr}\right] \right.$$

$$+\frac{1}{1+\alpha}\frac{B_\theta}{B_\phi}\frac{F_\theta^{W}}{n_e m_e} + \frac{\bar{\nu}_e}{1+\alpha}\frac{B_\theta}{B_\phi}u_{i\theta}$$

$$\left. -\left(\nu_{eb}-\frac{\alpha}{1+\alpha}\nu_{ei}\right)u_{b\phi} - \left(\nu_{ei}+\frac{\alpha}{1+\alpha}\nu_{eb}\right)u_{i\phi} \right\}$$

  - The first two terms in RHS are neoclassical resistivity and boot-strap current

- **Similar expression for poloidal rotation**

Model equations include dominant neoclassical transport.

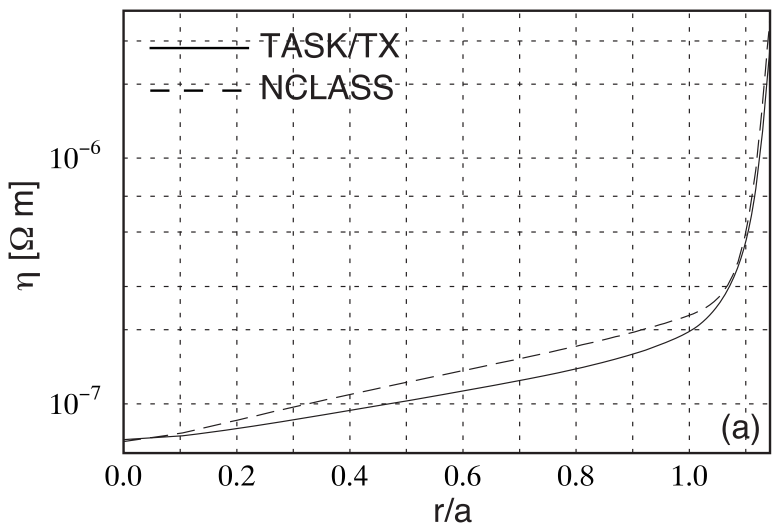
Recent Update of TASK/TX

- **Numerical scheme**
  - **Finite element method** (Linear interpolation, radial variable)
  - Streamline Upwind Petrov-Galerkin (SUPG) method
  - Choice of variables and boundary conditions
  - Improvement of numerical stability
  - Increase of spatial resolution
- **Neoclassical poloidal viscosity**
  - **Hirshman, Sigmar** $\longrightarrow$ **NCLASS**
- **SOL plasma model**
  - **Electron heat loss**: Thermal diffusion

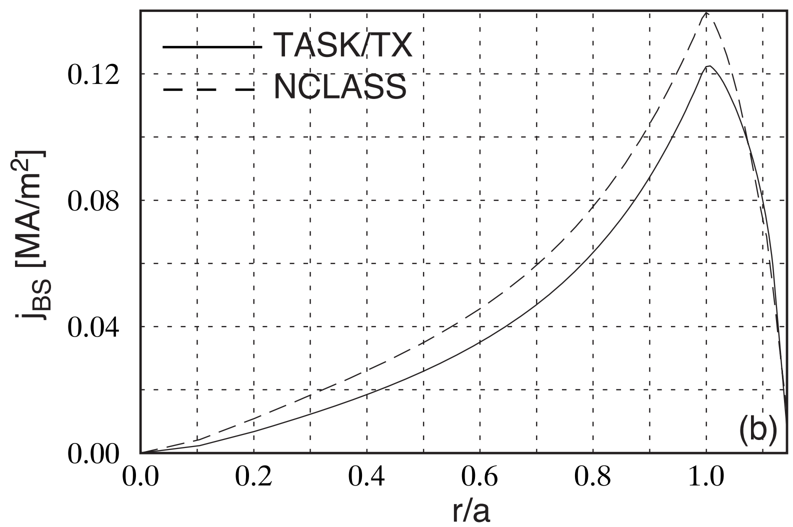
Neoclassical Effects

- **Comparison of resistivity and bootstrap current**
  - **Value Estimated from the steady state flux**
  - **Value calculated by NCLASS**

Resistivity



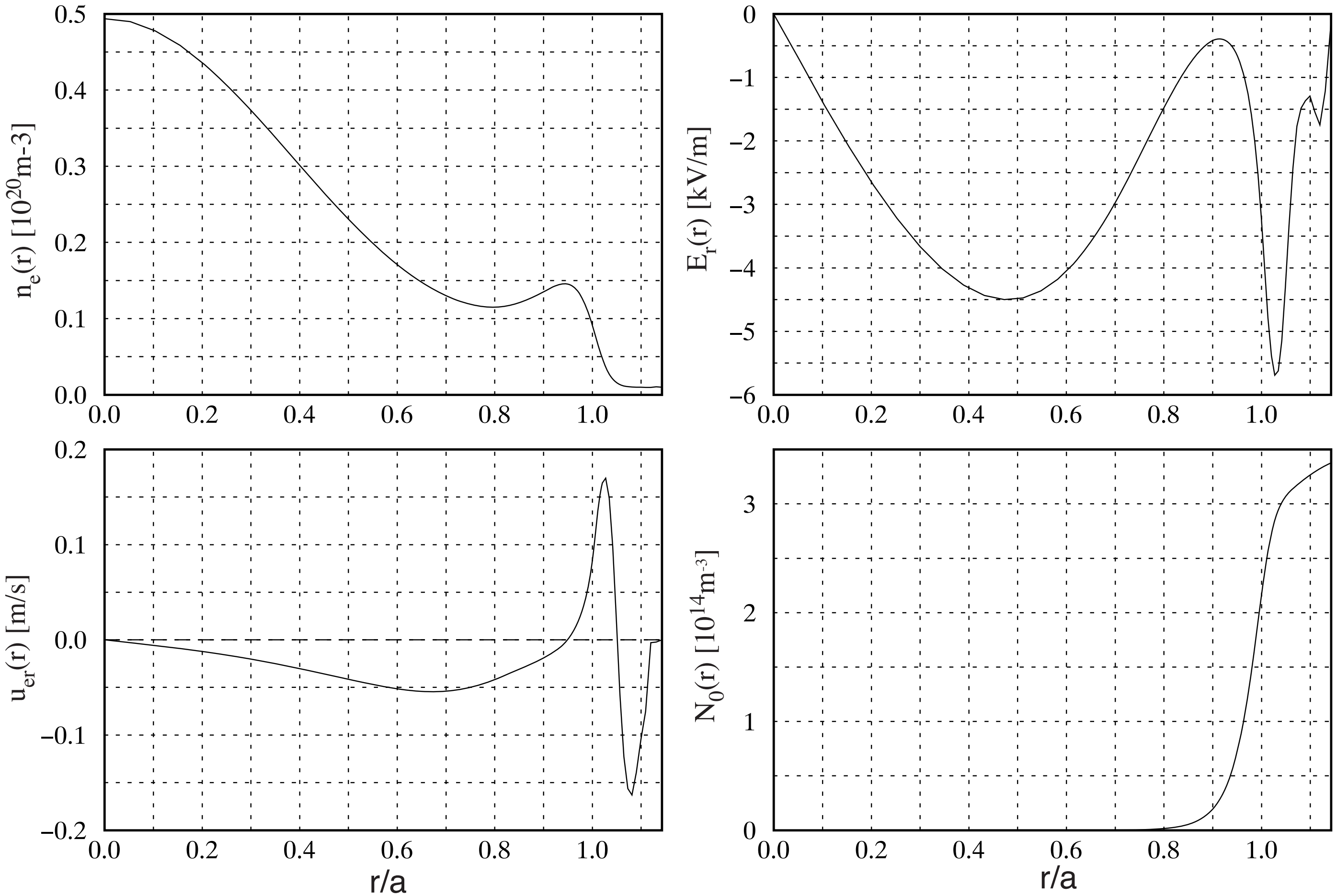
Bootstrap current



Neoclassical Transport (without turbulent transport)

Density

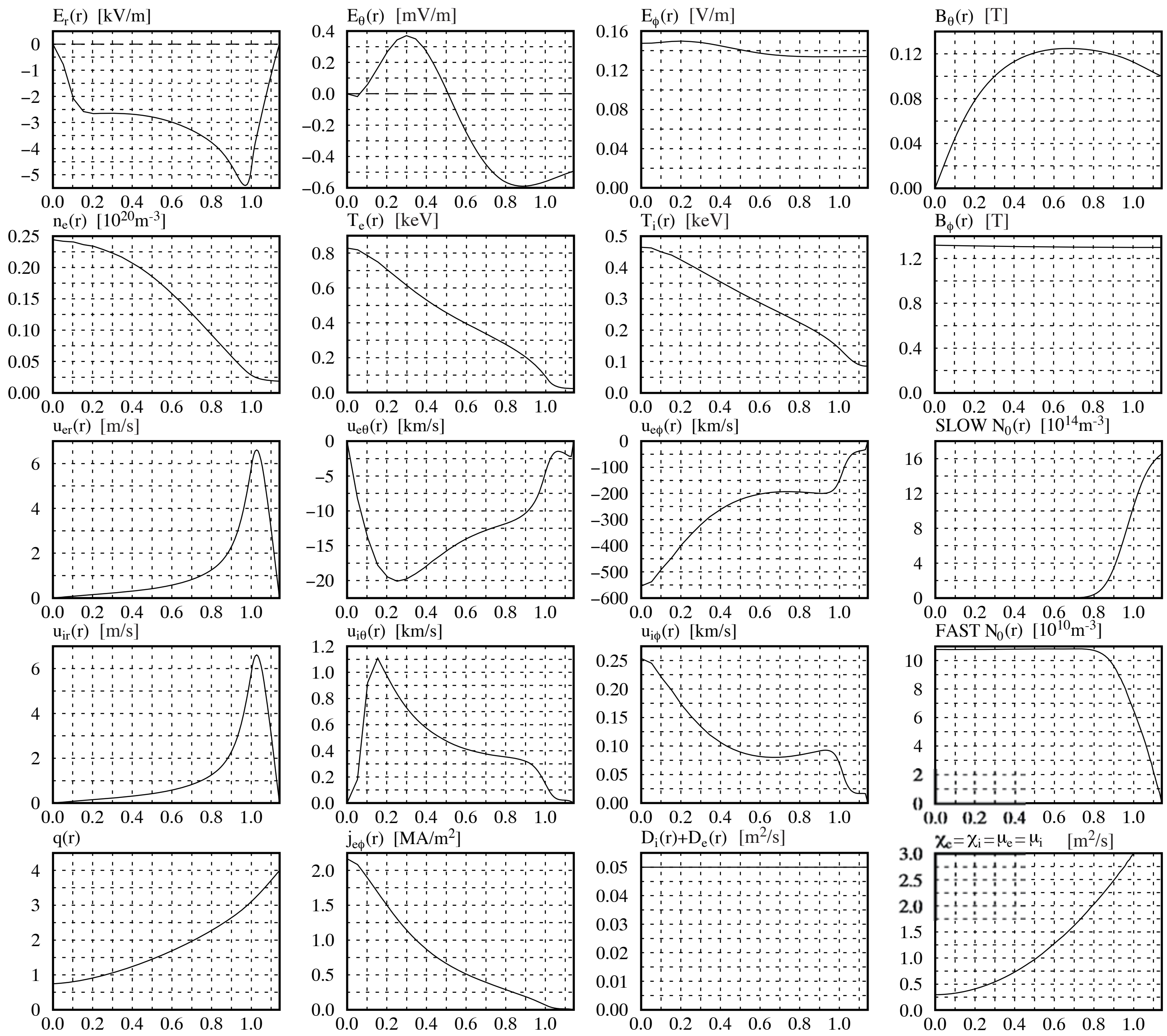
Radial electric field



Radial velocity

Neutral density

Typical Profiles (D_e: fixed parabolic profile)

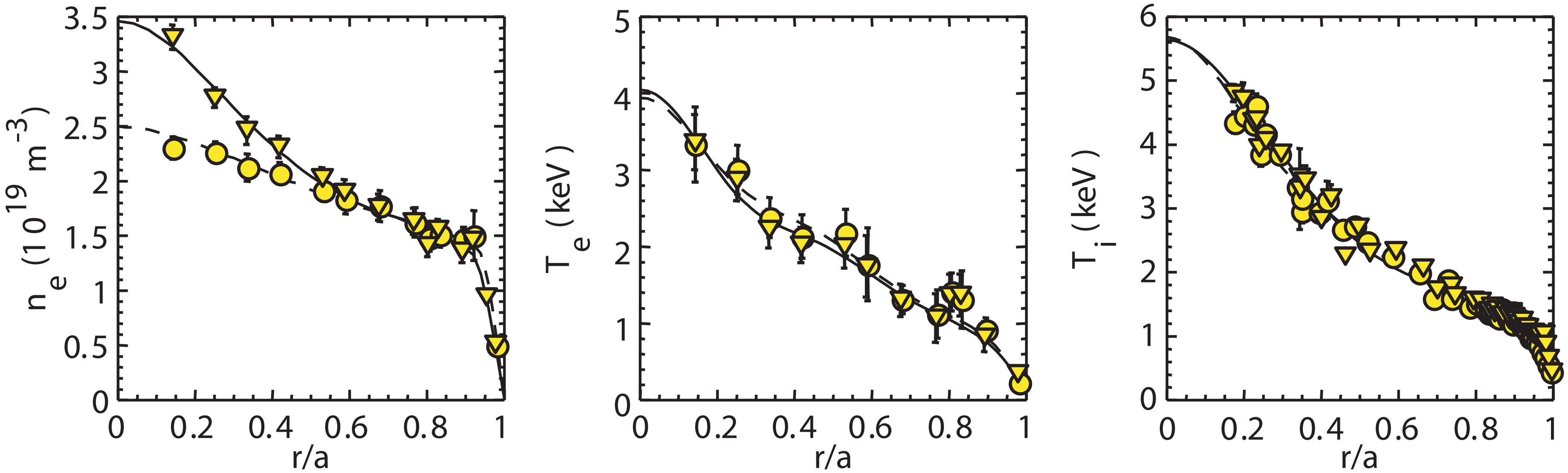


Density Peaking Due to Momentum Input

- Density peaking was observed in NBI counter injection on JT60-U.
  Ref. Takenaga et al. (ITPA, 2005)

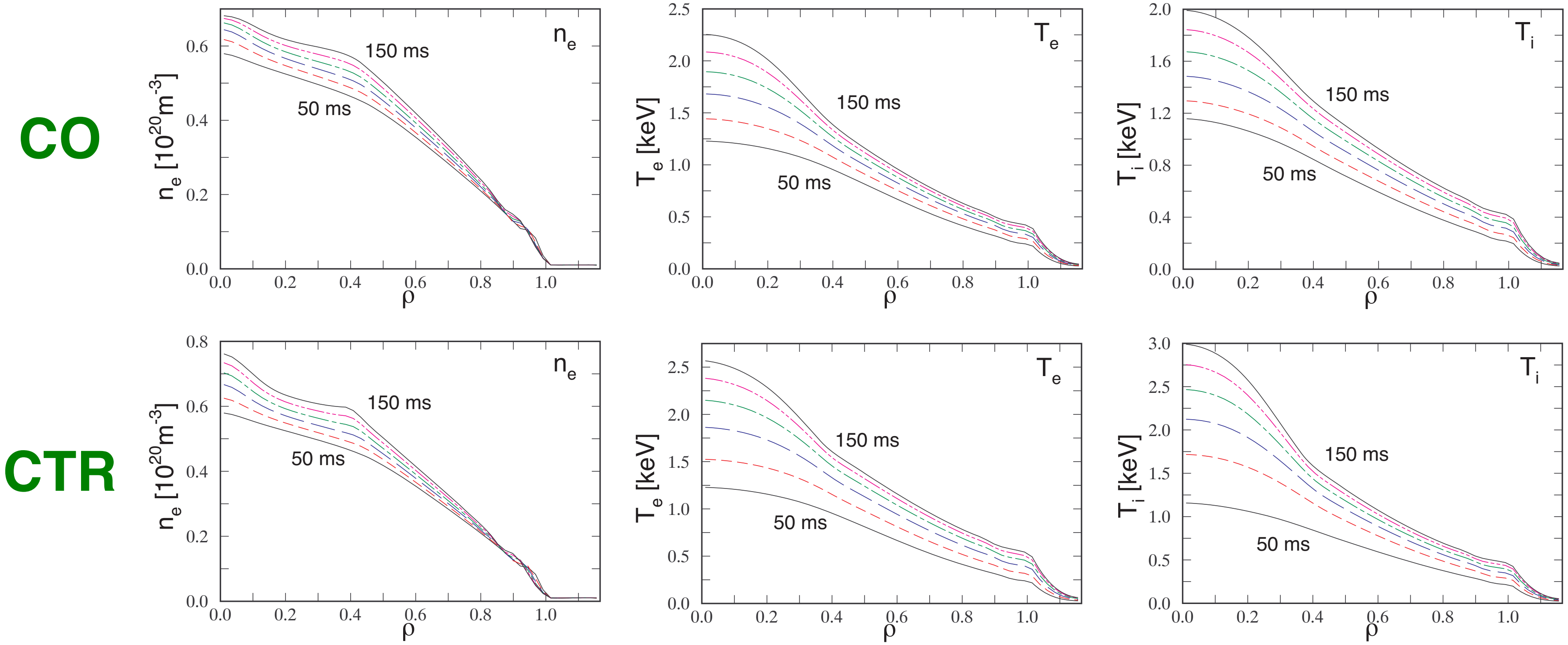
○ co-injection : $n_e(r/a=0.2)/ \langle n_e \rangle =1.41$
$P_{IN}=8.4MW$, $P_{ABS}=6.3MW$, $P_{LOSS}^{FAST}/P_{IN}=0.26$, $H_H^{98(y,2)}=0.86$

▽ ctr-injection : $n_e(r/a=0.2)/ \langle n_e \rangle =1.74$
$P_{IN}=10.2MW$, $P_{ABS}=6.5MW$, $P_{LOSS}^{FAST}/P_{IN}=0.38$, $H_H^{98(y,2)}=0.81$



Density Peaking Simulation (TASK/TR: old version)

- Transport model: CDBM (particle diffusivity, thermal diffusivity)
- **NBI $6.5\,\mathrm{MW}$** was injected $50\,\mathrm{ms}$ after the simulation started.
- **Simulation results**
  - **$n(0)$ for co injection is 12% higher than that for counter inj.**
  - **Temperature is higher for counter injection $\leftrightarrow$ experiments**



Extension to TASK/3D

- **3D Equilibrium**:
  - **Interface to equilibrium data from VMEC or HINT**
  - **Interface to neoclassical transport coefficient codes**
- **Modules 3D-ready**:
  - **WR**: Ray and beam tracing
  - **WM**: Full wave analysis
- **Modules to be updated**:
  - **TR**: Diffusive transport (with an appropriate model of E_r)
  - **TX**: Dynamical transport (with neoclassical toroidal viscosity)
  - **FP**: Fokker-Planck analysis (with helical ripple trapping)
- **Modules to be added**: (**by Y. Nakamura**)
  - **EI**: Time evolution of current profile in helical geometry

Future Plan of TASK code

	Present Status	In 2 years	In 5 years
Equlibrium	Fixed/Free Boundary	Equilibrium Evolution	Start Up Analysis
Core Transport	1D Diffusive TR	Kinetic TR	2D Fluid TR
	1D Dynamic TR		
SOL Transport		2D Fluid TR	Plasma-Wall Interaction
Neutral Tranport	1D Diffusive TR	Orbit Following	
Energetic Ions	Kinetic Evolution	Orbit Following	
Wave Beam	Ray/Beam Tracing	Beam Propagation	
Full Wave	Kinetic ϵ	Gyro Integral ϵ	Orbit Integral ϵ
Stabilities	Sawtooth Osc.	Tearing Mode	Systematic Stability Analysis
	ELM Model	Resistive Wall Mode	
Turbulent Transport	CDBM Model	Linear GK + ZF	Nonlinear ZK + ZF
		Diagnostic Module	
		Control Module	

Summary

- We are developing **TASK** code as a reference core code for burning plasma simulation based on transport analysis.
- Preliminary results of **self-consistent analysis of wave heating and current drive** describing the time evolution of the momentum distribution function and its influence on the wave propagation and absorption have been obtained.
- Simulations of **ITER advanced scenarios** requires further benchmark tests
- Dynamical transport module **TASK/TX** was significantly improved on the numerical scheme and the transport model. Barrier formation and density modification will be studied.
- **Extension to 3D configuration** is on-going in collaboration with Dr. Y. Nakamura and NIFS.

Model Equation (1)

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

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

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

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

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

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

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

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

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

Model Equation (2)

- **Diffusion equation for (fast and slow) neutral particles**

$$\frac{\partial n_0}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r}\left(-rD_0\frac{\partial n_0}{\partial r}\right) + S_0$$

- **Maxwell's equation**

$$\frac{1}{r}\frac{\partial}{\partial r}(rE_r) = \frac{1}{\epsilon_0}\sum_s e_s n_s$$

$$\frac{\partial B_\theta}{\partial t} = \frac{\partial E_\phi}{\partial r}, \qquad \frac{\partial B_\phi}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r}(rE_\phi)$$

$$\frac{1}{c^2}\frac{\partial E_\theta}{\partial t} = -\frac{\partial}{\partial r}B_\phi - \mu_0\sum_s e_s n_s u_{s\theta}, \qquad \frac{1}{c^2}\frac{\partial E_\phi}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}(rB_\theta) - \mu_0\sum_s e_s n_s u_{s\phi}$$