Workshop on Kinetic Theory in Stellarators
Kyoto University, 2006/09/20

TASK: Integrated Simulation Code

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Contents

- BPSI: Burning Plasma Simulation Initiative
- TASK: Core Code for Integrated Modeling
- Consideration on TASK/3D
- Summary

Burning Plasma Simulation

- **Why needed?**
  - To predict the behavior of burning plasmas
  - To develop reliable and efficient schemes to control them

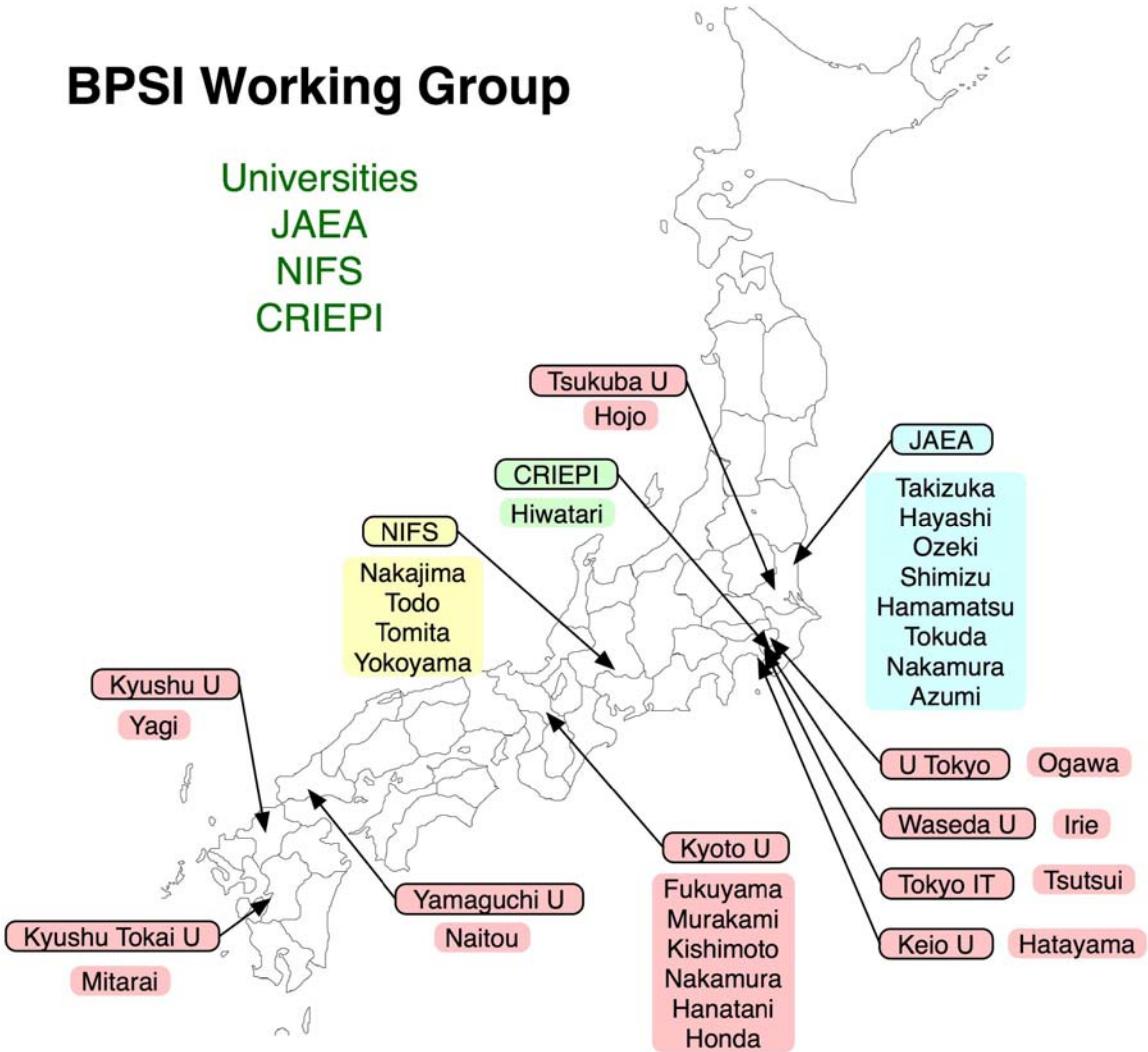
- **What is needed?**
  - **Simulation describing a burning plasma:**
    - **Whole plasma** (core & edge & divertor & wall-plasma)
    - **Whole discharge**
      (startup & sustainment & transients events & termination)
    - **Reasonable accuracy** (validation with experimental data)
    - **Reasonable computer resources** (still limited)

- **How can we do?**
  - **Gradual increase of understanding and accuracy**
  - **Organized development of simulation system**

BPSI: Burning Plasma Simulation Initiative

Research Collaboration among Universities, NIFS and JAEA

Since 2002

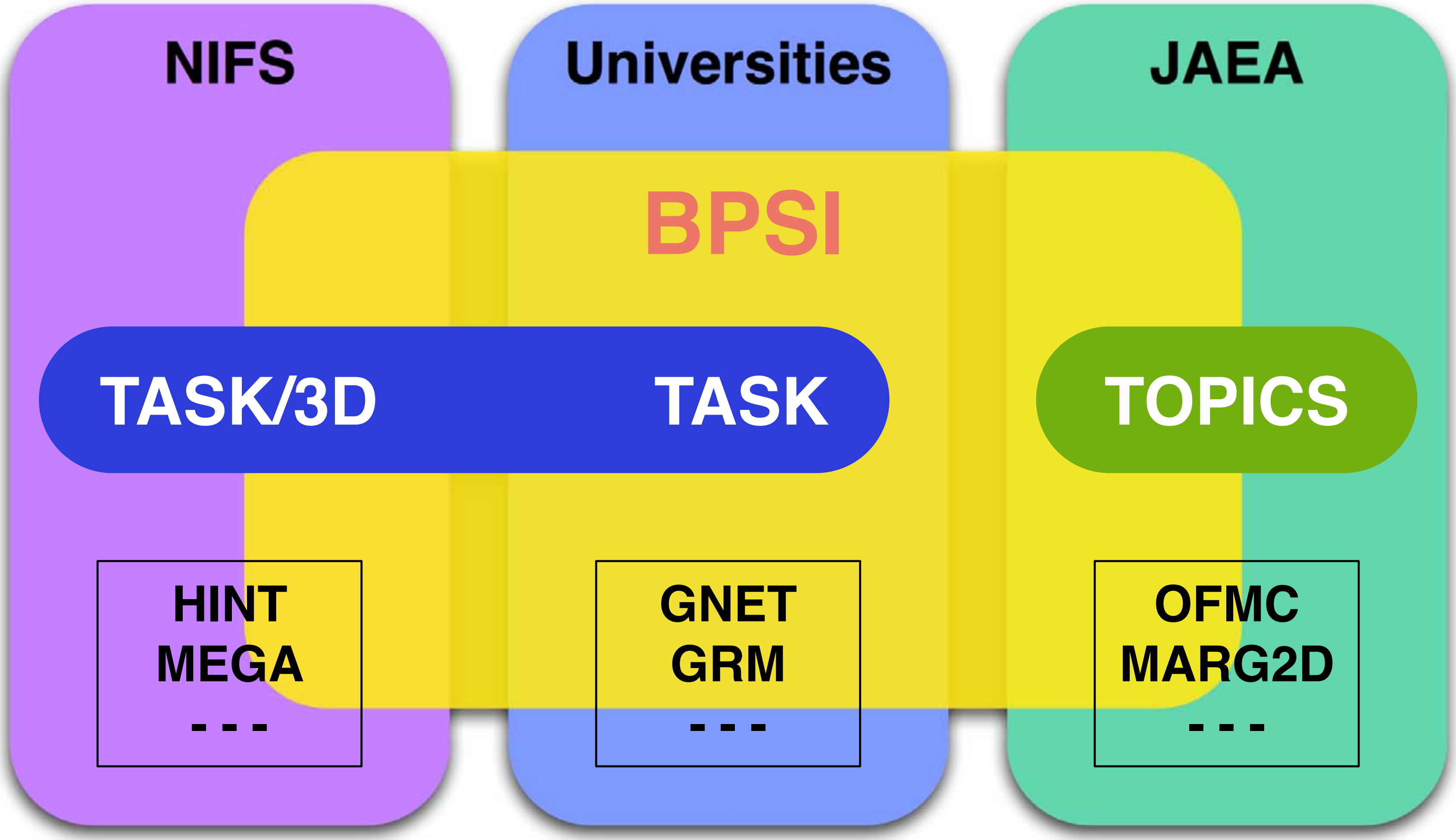


Targets of BPSI

- **Framework** for collaboration of various plasma simulation codes
  - **Common interface** for data transfer and execution control
  - **Standard data set** for data transfer and data storage
  - **Reference core code**: TASK
  - **Helical configuration**: included
- **Physics integration** with different time and space scales
  - **Transport during and after a transient MHD events**
  - **Transport in the presence of magnetic islands**
  - **Core-SOL interface** and . . .
- **Advanced technique** of computer science
  - **Parallel computing**: PC cluster, Scalar-Parallel, Vector-Parallel
  - **Distributed computing**: GRID computing, Globus, ITBL

Integrated Code Development Based on BPSI Framework

Integrated code: TASK and TOPICS



TASK Code

- **Transport Analysing System for TokamaK**
- **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**
    - Most of library routines included (except LAPACK and MPI)
    - Own graphic libraries (X11, eps, OpenGL)
  - **Development using CVS** (Concurrent Version System)
    - Open Source (Pre-release with f77: http://bpsi.nucleng.kyoto-u.ac.jp/task/)
  - **Parallel Processing using MPI Library**
  - **Extension to Toroidal Helical Plasmas**

Modules of TASK

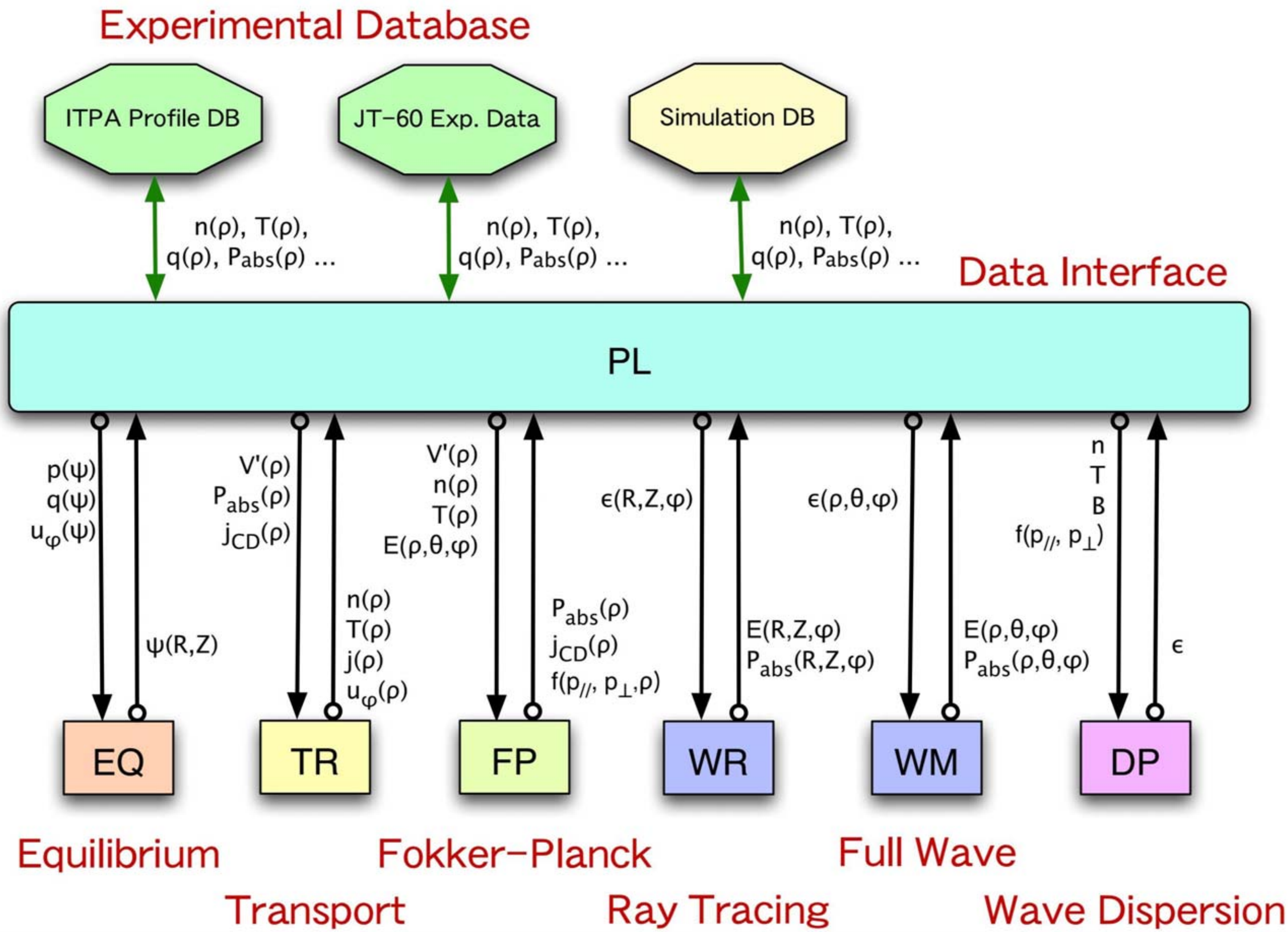
EQ	**2D Equilibrium**	Fixed/Free boundary, Toroidal rotation
TR	**1D Transport**	Diffusive transport, Transport models
WR	**3D Geometr. Optics**	EC, LH: Ray tracing, Beam tracing
WM	**3D Full Wave**	IC, AW: Antenna excitation, Eigen mode
FP	**3D Fokker-Planck**	Relativistic, Bounce-averaged
DP	**Wave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

Under Development

`TX`	Transport analysis including plasma rotation and E_r
`WA`	Global linear stability analysis
`WI`	Integro-differential wave analysis (FLR, $\boldsymbol{k} \cdot \nabla B \neq 0$)

All developed in Kyoto U

Modular Structure of TASK



Data Interface Layer PL

- **Role of Interface Layer**
  - To keep the present status of plasma
  - To store the history of plasma
  - Interface to file system
  - Interface to experimental profile database
  - Interface to simulation profile database
- **Data to be stored**
  - **Standard dataset**
    - Shot data, Device data
    - Equilibrium data, Metric data
    - Fluid plasma data, Kinetic plasma data
    - Dielectric tensor data, Full wave data, Ray/Beam tracing data
  - **User-defined data**

Standard Dataset (interim)

Shot data

Machine ID, Shot ID, Model ID

Device data: (Level 1)

RR	R	m	Geometrical major radius
RA	a	m	Geometrical minor radius
RB	b	m	Wall radius
BB	B	T	Vacuum toroidal mag. field
RKAP	κ		Elongation at boundary
RDLT	δ		Triangularity at boundary
RIP	I_p	A	Typical plasma current

Equilibrium data: (Level 1)

PSI2D	$\psi_\mathrm{p}(R,Z)$	Tm^2	2D poloidal magnetic flux
PSIT	$\psi_\mathrm{t}(\rho)$	Tm^2	Poloidal magnetic flux
PSIP	$\psi_\mathrm{p}(\rho)$	Tm^2	Poloidal magnetic flux
PPSI	$p(\rho)$	MPa	Plasma pressure
TPSI	$T(\rho)$	Tm	$B_\phi R$
QPSI	$1/q(\rho)$		Safety factor

Metric data

1D: $V'(\rho)$, $\langle\nabla V\rangle(\rho)$, $\cdots$

2D: g_{ij}, $\cdots$

3D: g_{ij}, $\cdots$

Fluid plasma data

NSMAX	s		Number of particle species
PA	A_s		Atomic mass
PZ0	Z_{0s}		Charge number
PZ	Z_s		Charge state number
PN	$n_s(\rho)$	m^3	Number density
PT	$T_s(\rho)$	eV	Temperature
PU	$u_{s\phi}(\rho)$	m/s	Toroidal rotation velocity

Kinetic plasma data

FP	$f(p,\theta_p,\rho)$		momentum dist. fn at $\theta=0$

Dielectric tensor data

CEPS	$\overleftrightarrow{\epsilon}(\rho,\chi,\zeta)$		Local dielectric tensor

Full wave field data

CE	$\boldsymbol{E}(\rho,\chi,\zeta)$	V/m	Complex wave electric field
CB	$\boldsymbol{B}(\rho,\chi,\zeta)$	$\mathrm{Wb/m}^2$	Complex wave magnetic field

Ray/Beam tracing field data

RRAY	$R(\ell)$	m	R of ray at length ℓ
ZRAY	$Z(\ell)$	m	Z of ray at length ℓ
PRAY	$\phi(\ell)$	rad	ϕ of ray at length ℓ
CERAY	$\boldsymbol{E}(\ell)$	V/m	Wave electric field at length ℓ
PWRAY	$\boldsymbol{P}(\ell)$	W	Wave power at length ℓ
DRAY	$\boldsymbol{d}(\ell)$	m	Beam radius at length ℓ
VRAY	$\boldsymbol{v}(\ell)$	1/m	Beam curvature at length ℓ

Execution Control Interface in BPSI

- **Example for TASK/TR**

`TR_INIT`	Initialization (Default value)	`BPSX_INIT('TR')`
`TR_PARM(ID,PSTR)`	Parameter setup (Namelist input)	`BPSX_PARM('TR',ID,PSTR)`
`TR_PROF(T)`	Profile setup (Spatial profile, Time)	`BPSX_PROF('TR',T)`
`TR_EXEC(DT)`	Exec one step (Time step)	`BPSX_EXEC('TR',DT)`
`TR_GOUT(PSTR)`	Plot data (Plot command)	`BPSX_GOUT('TR',PSTR)`
`TR_SAVE`	Save data in file	`BPSX_SAVE('TR')`
`TR_LOAD`	load data from file	`BPSX_LOAD('TR')`
`TR_TERM`	Termination	`BPSX_TERM('TR')`

- **Module registration**

```
TR_STRUCT%INIT=TR_INIT
TR_STRUCT%PARM=TR_PARM
TR_STRUCT%EXEC=TR_EXEC
   ...
BPSX_REGISTER('TR',TR_STRUCT)
```

Full wave analysis: TASK/WM

- **magnetic surface coordinate**: (ψ, θ, φ)
- Boundary-value problem of **Maxwell's equation**

$$\nabla \times \nabla \times \boldsymbol{E} = \frac{\omega^2}{c^2} \overleftrightarrow{\epsilon} \cdot \boldsymbol{E} + \mathrm{i}\,\omega\mu_0 \boldsymbol{j}_{\mathrm{ext}}$$

- Kinetic **dielectric tensor**: $\overleftrightarrow{\epsilon}$
  - **Wave-particle resonance**: $Z[(\omega - n\omega_{\mathrm{c}})/k_{\|}v_{\mathrm{th}}]$
  - **Fast ion: Drift-kinetic**

$$\left[\frac{\partial}{\partial t} + v_{\|}\nabla_{\|} + (\boldsymbol{v}_{\mathrm{d}} + \boldsymbol{v}_{\mathrm{E}}) \cdot \nabla + \frac{e_\alpha}{m_\alpha}(v_{\|}E_{\|} + \boldsymbol{v}_{\mathrm{d}} \cdot \boldsymbol{E})\frac{\partial}{\partial \varepsilon}\right] f_\alpha = 0$$

- Poloidal and toroidal **mode expansion**
  - **Accurate estimation of $k_{\|}$**
- Eigenmode analysis: **Complex eigen frequency** which maximize wave amplitude for fixed excitation proportional to electron density

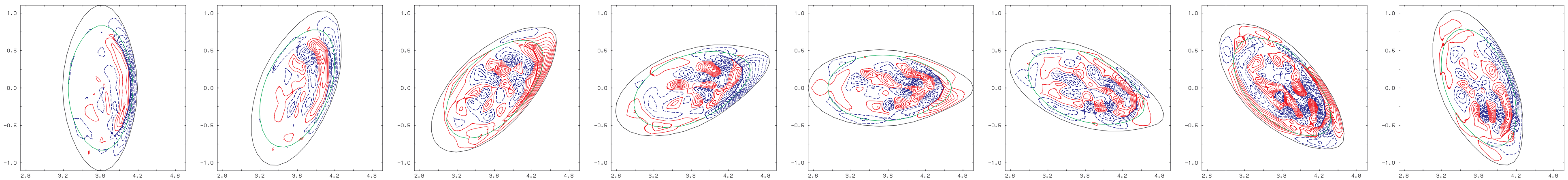
ICRF Waves in Toroidal Helical Plasmas
(Cold Plasma Model)

LHD ($B_0 = 3\,\mathrm{T}$, $R_0 = 3.8\,\mathrm{m}$)

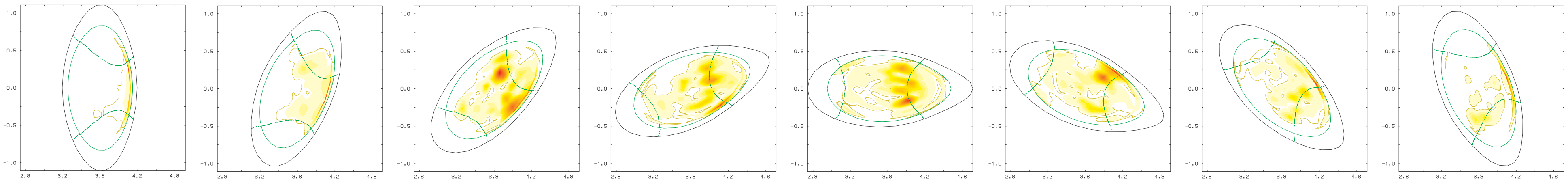
$f = 42\,\mathrm{MHz}$, $n_{\phi 0} = 20$, $n_{e0} = 3 \times 10^{19}\,\mathrm{m}^{-3}$, $n_H/(n_{He} + n_H) = 0.235$,

$N_{r\max} = 100$, $N_{\theta\max} = 16$ ($m = -7 \ldots 7$), $N_{\phi\max} = 4$ ($n = 10, 20, 30$)

Wave electric field (imaginary part of poloidal component)



Power deposition profile (minority ion)



Fokker-Planck Analysis : TASK/FP

- **Fokker-Planck equation**

  for **velocity distribution function** $f(p_{||}, p_\perp, \psi, t)$

$$\frac{\partial f}{\partial t} = E(f) + C(f) + Q(f) + L(f)$$

  - $E(f)$: Acceleration term due to DC electric field
  - $C(f)$: Coulomb collision term
  - $Q(f)$: Quasi-linear term due to wave-particle resonance
  - $L(f)$: Spatial diffusion term

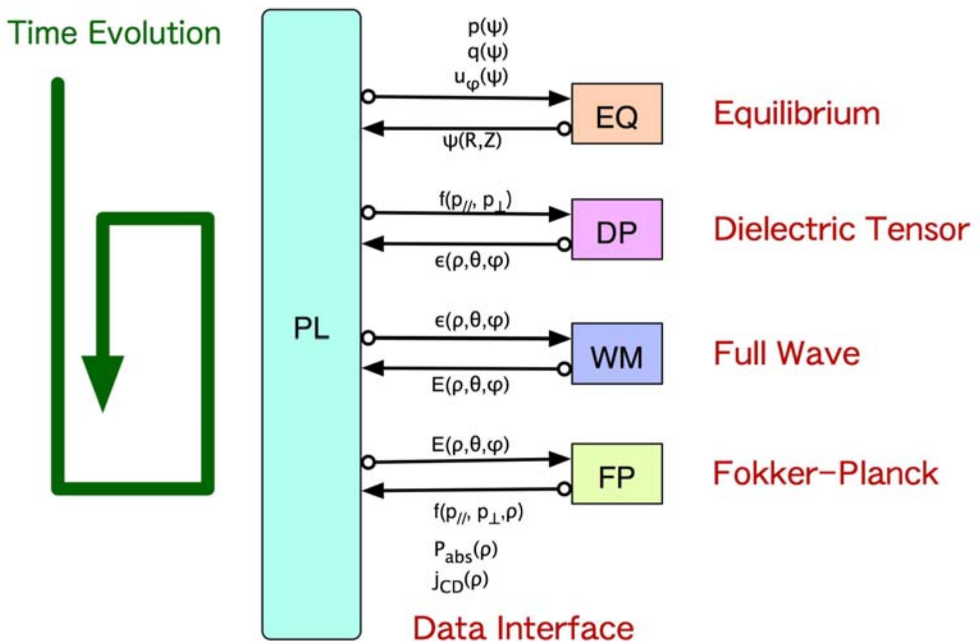
- **Bounce-averaged**: Trapped particle effect, zero banana width
- **Relativistic**: momentum $\boldsymbol{p}$, weakly relativistic collision term
- **Nonlinear collision**: momentum or energy conservation
- **Three-dimensional**: spatial diffusion (neoclassical, turbulent)

Wave Dispersion Analysis : TASK/DP

- **Various Models of Dielectric Tensor $\overleftrightarrow{\epsilon}(\omega, \boldsymbol{k}; \boldsymbol{r})$:**
  - Resistive MHD model
  - Collisional cold plasma model
  - Collisional warm plasma model
  - Kinetic plasma model (Maxwellian, non-relativistic)
  - Kinetic plasma model (Arbitrary $f(\boldsymbol{v})$, relativistic)
  - Gyro-kinetic plasma model (Maxwellian)
  - Gyro-kinetic plasma model (Arbitrary $f(\boldsymbol{v})$, non-relativistic)
- **Arbitrary $f(\boldsymbol{v})$:**
  - Relativistic Maxwellian
  - Output of TASK/FP

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 $f(v)$**

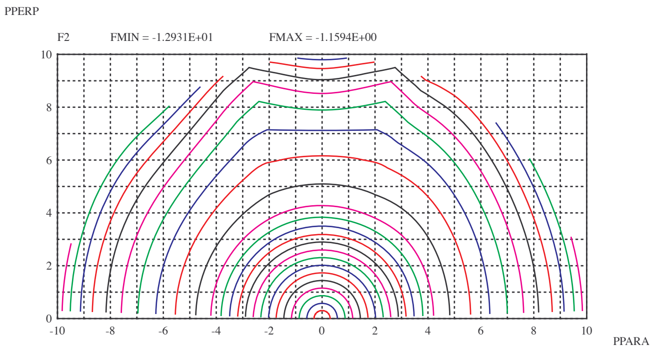


Development of Self-Consistent Wave Analysis

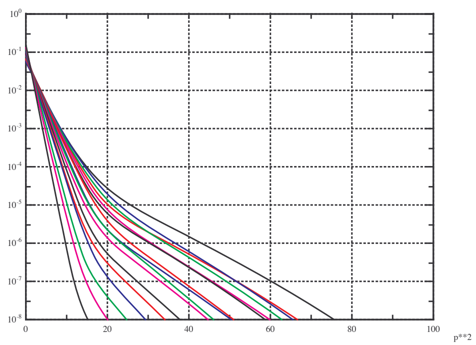
- **Code Development in TASK**
  - Ray tracing analysis with arbitrary $f(v)$: **Already done**
  - Full wave analysis with arbitrary $f(v)$: **Completed**
  - Fokker-Plank analysis of ray tracing results: **Already done**
  - Fokker-Plank analysis of full wave results: **Almost competed**
  - Self-consistent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

- **Tail formation by ICRF minority heating**

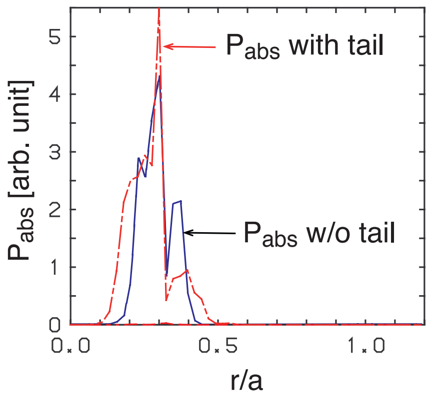
Momentum Distribution



Tail Formation



Power deposition



Diffusive Transport Analysis: TASK/TR

- **Transport Equation Based on Gradient-Flux Relation**
  - **Multi thermal species**: e.g. Electron, D, T, He
  — Density, thermal energy, (toroidal rotation)
  - **Two beam components**: Beam ion, Energetic α
  — Density, toroidal rotation
  - **Neutral**: Two component (cold and hot), Diffusion equation
  - **Impurity**: Thermal species or fixed profile
- **Transport Model**
  - **Neoclassical**: Wilson, Hinton & Hazeltine, Sauter, NCLASS
  - **Turbulent**: CDBM (current diffusive ballooning mode), GLF23 (V1.61), IFS/PPPL, Weiland
- **Interface to Experimental Data**
  - UFILE (ITPA profile DB)

CDBM Transport Model: CDBM05

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

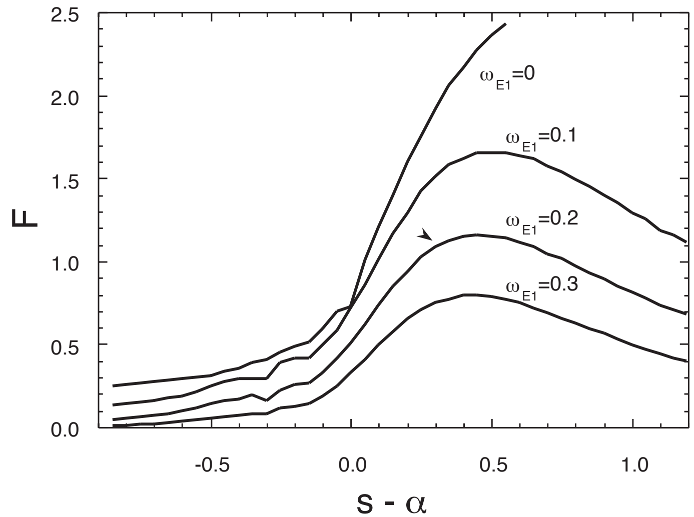
$$\chi_{\mathrm{TB}} = F(s, \alpha, \kappa, \omega_{\mathrm{E1}})\,\alpha^{3/2}\,\frac{c^2}{\omega_{\mathrm{pe}}^2}\,\frac{v_{\mathrm{A}}}{qR}$$

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

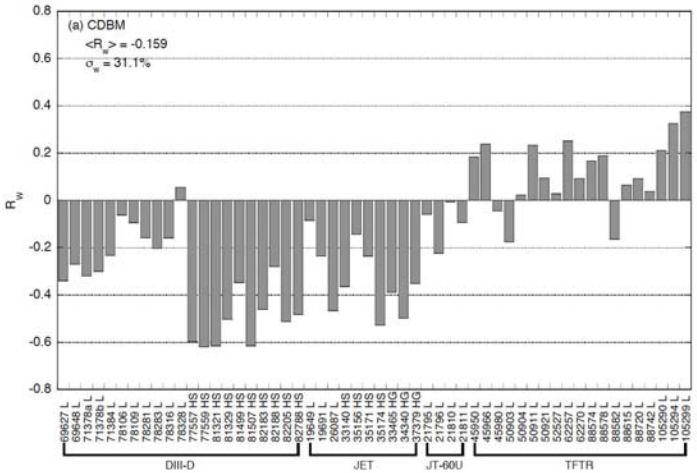


$$F(s, \alpha, \kappa, \omega_{\mathrm{E1}}) = \left(\frac{2\kappa^{1/2}}{1+\kappa^2}\right)^{3/2} \times \begin{cases} \dfrac{1}{1+G_1\omega_{\mathrm{E1}}^2}\dfrac{1}{\sqrt{2(1-2s')(1-2s'+3s'^2)}} & \text{for } s' = s-\alpha < 0 \\[2ex] \dfrac{1}{1+G_1\omega_{\mathrm{E1}}^2}\dfrac{1+9\sqrt{2}s'^{5/2}}{\sqrt{2}(1-2s'+3s'^2+2s'^3)}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

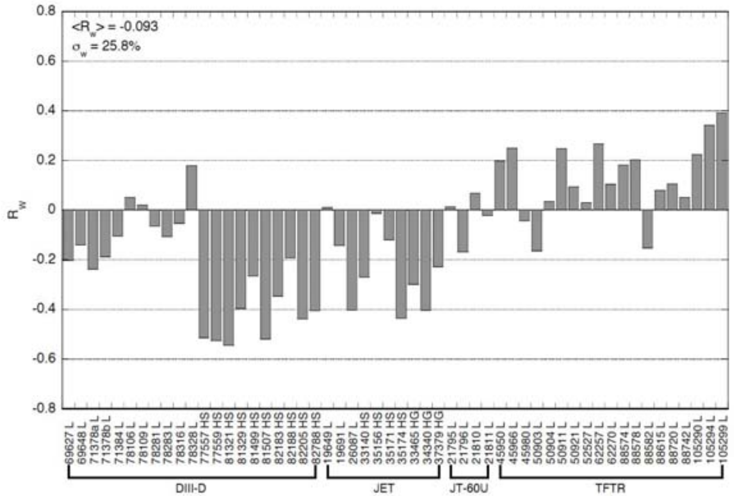
Comparison of Transport Models: ITPA Profile DB

Deviation of Stored Energy

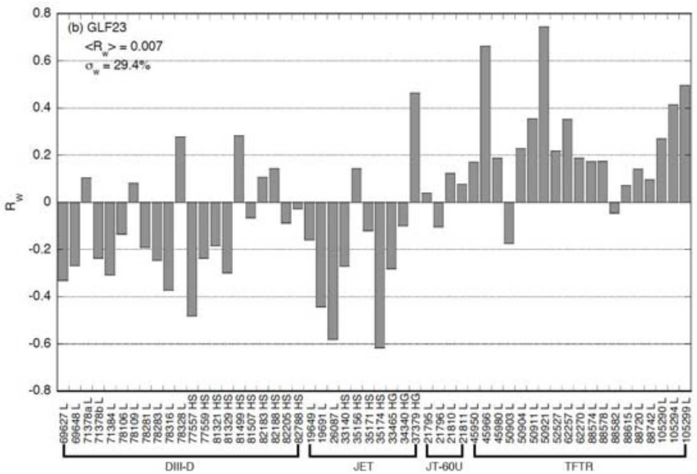
CDBM



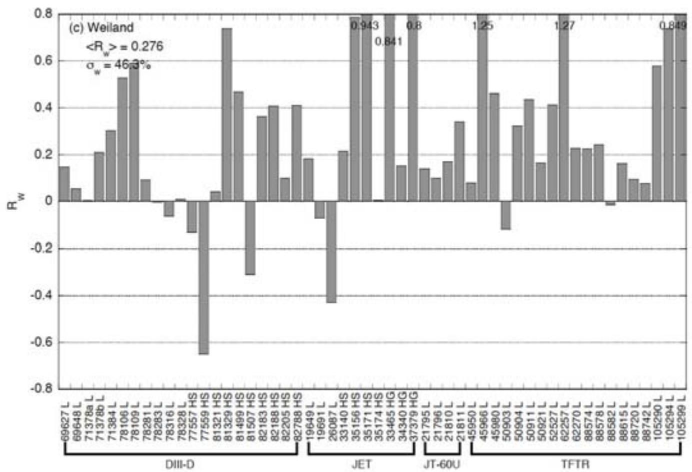
CDBM05



GLF23

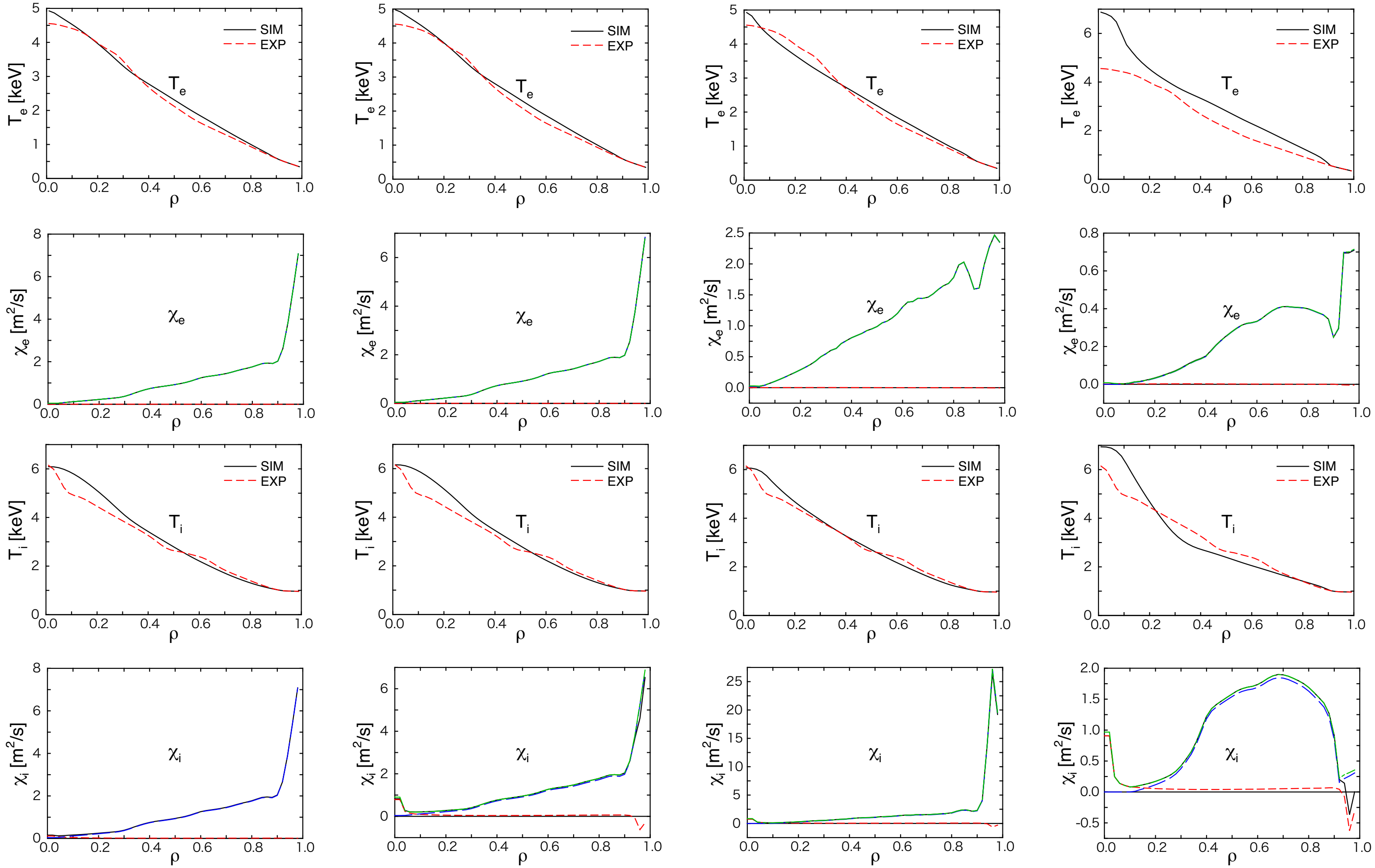


Weiland

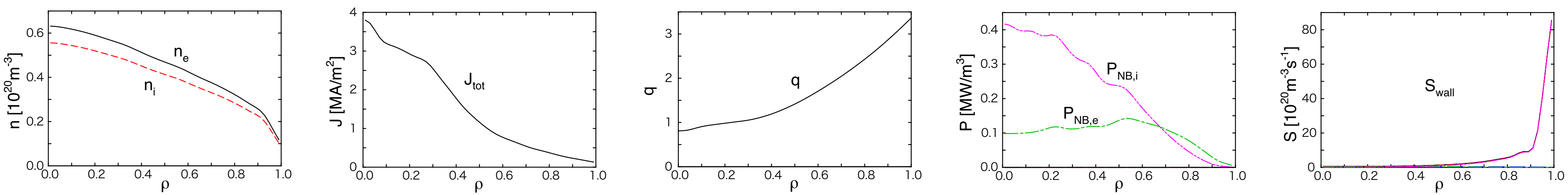


TFTR #88615 (L-mode, NBI heating)

CDBM | CDBM05 | GLF23 | Weiland

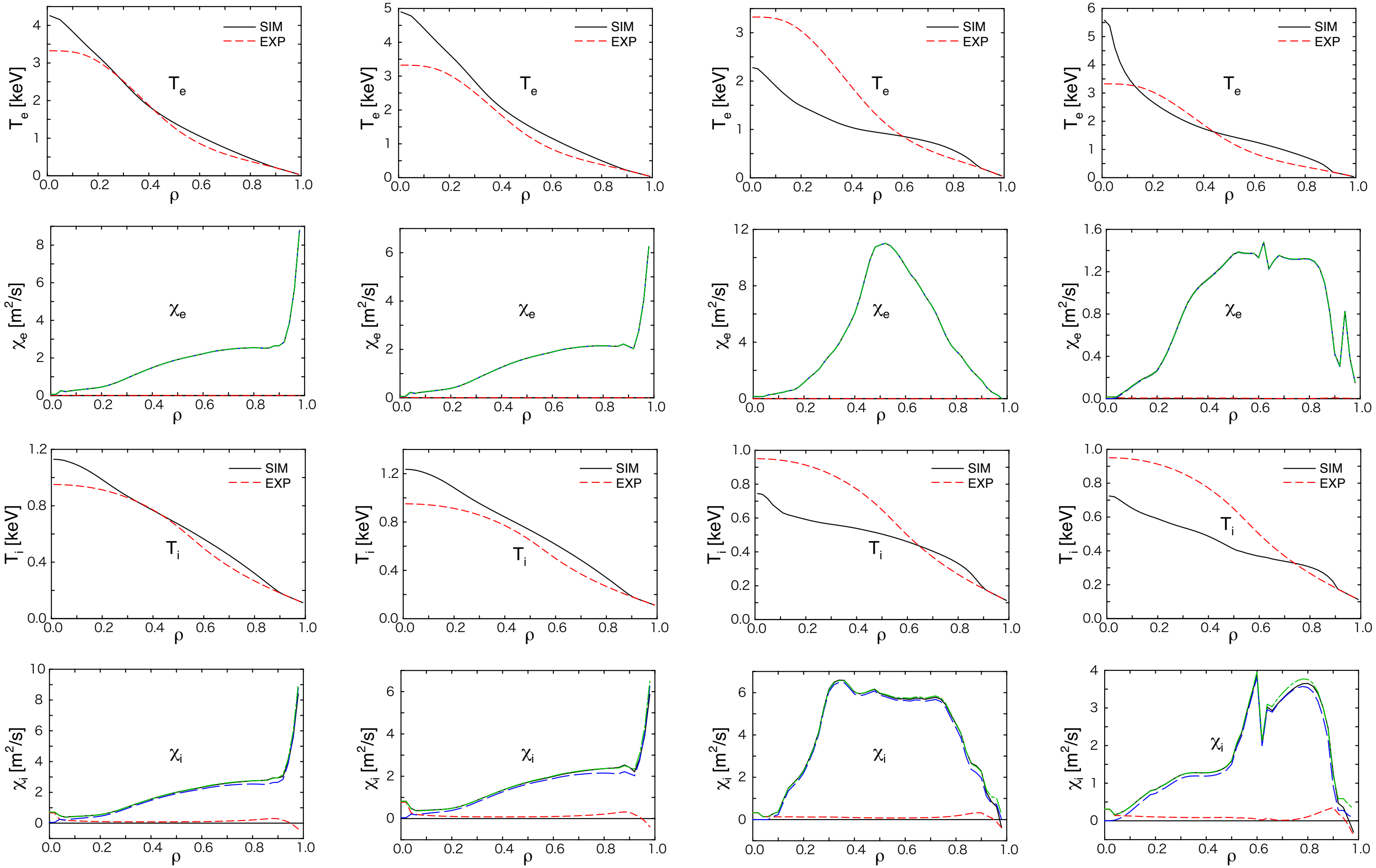


Common Profiles

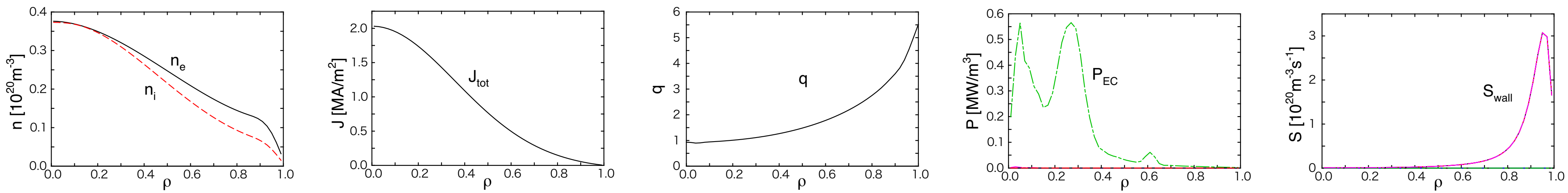


DIII-D #78316 (L-mode, ECH and ICH heatings)

CDBM | CDBM05 | GLF23 | Weiland



Common Profiles



1D Transport code: TASK/TX

- **Dynamic Transport Equation**: *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
  - **Maxwell's equation, Poisson's equation**
  - **Slowdown equation for beam component**
  - **Diffusion equation for neutral particles**

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**

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

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

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

Neoclassical Transport Model

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

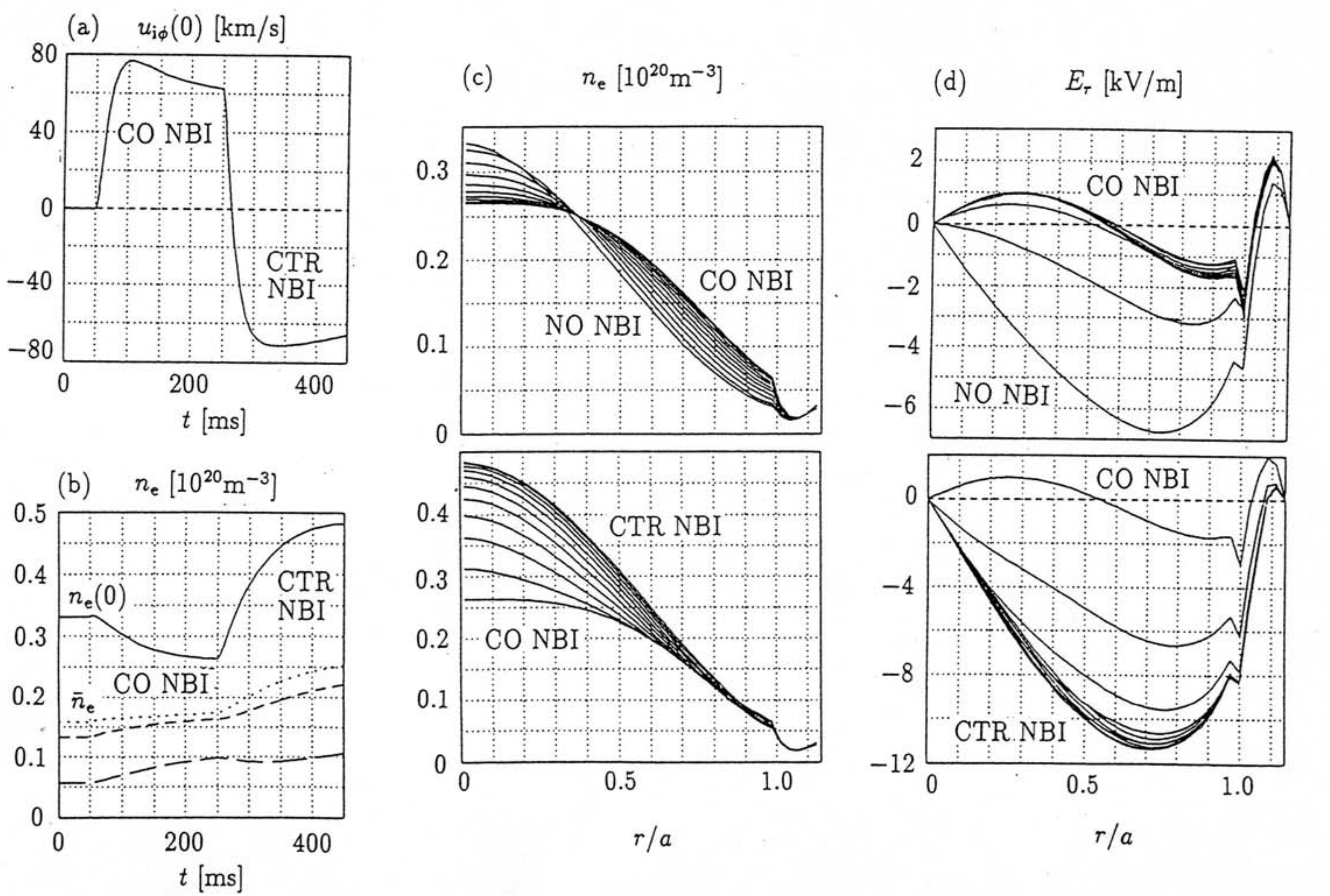
$$F_{s\theta}^{\mathrm{NC}} = -\sqrt{\pi} q^2 n_s m_s \frac{v_{\mathrm{T}s}}{qR} \frac{\nu_s^*}{1+\nu_s^*} u_{s\theta}$$

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

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

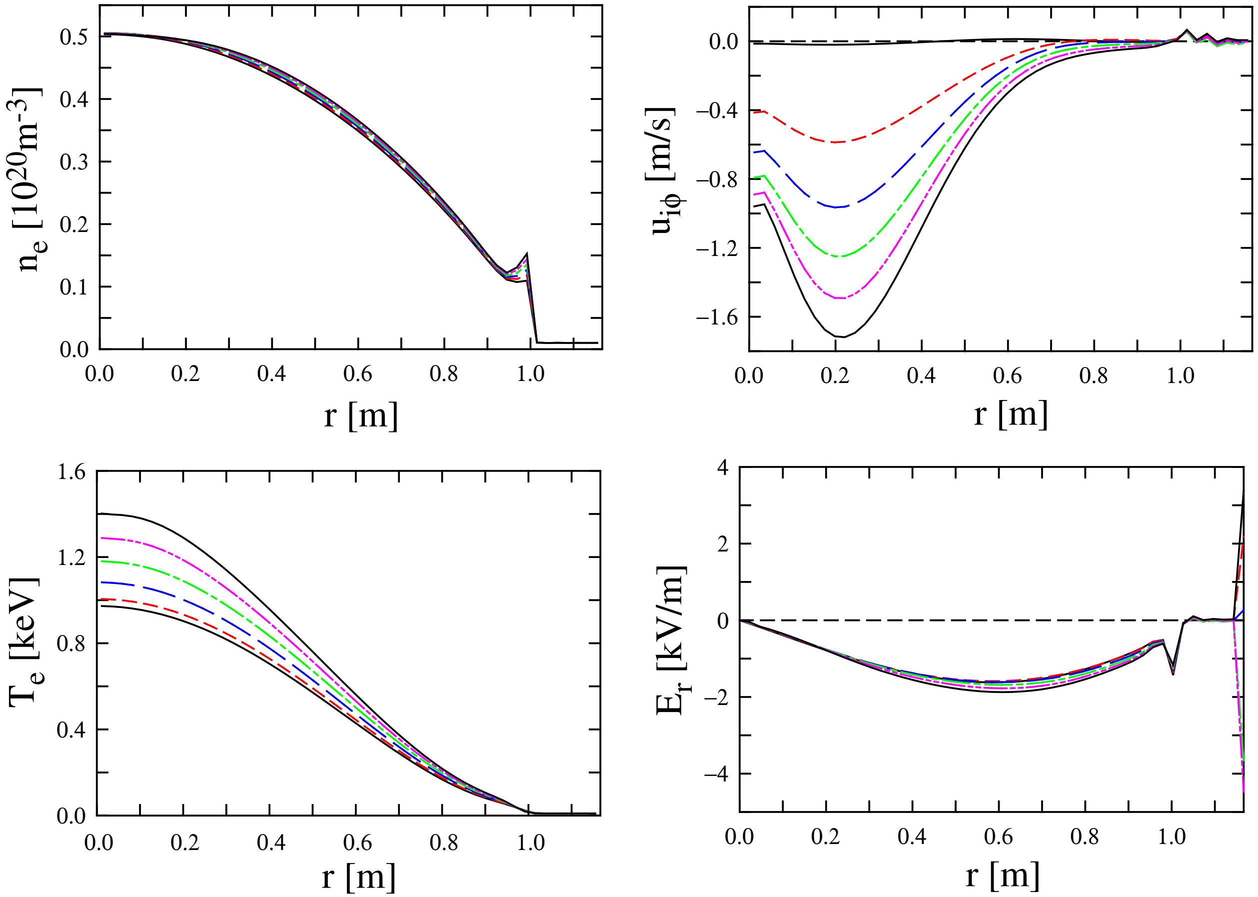
Simulation of plasma rotation and radial electric field

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



Transport Modeling in Helical Plasma

- **Neoclassical toroidal viscosity**
- **Negative magnetic shear**
- **Preliminary Result**
  - **NBI heating** ($P = 5\,\mathrm{MW}$) **: Order of magnitude slower rotation**



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	

Extension to TASK/3D

- **3D Equilibrium**:
  - **Interface to equilibrium data from VMEC or HINT**
- **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**:
  - **EI**: Time evolution of current profile in helical geometry

Summary

- We are developing **TASK** code as a reference core code for burning plasma simulation based on transport analysis.
- **Standard dataset** and **module interface** are being implemented.
- 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.
- **Extension to 3D configuration** is on-going in collaboration with Dr. Y. Nakamura and NIFS. **(See Next Presentation)**

Access to TASK code

- **Required Environment**
  - Unix-like OS (Linux, Mac OSX, $\cdots$)
  - X-window system
  - Fortran95 compiler (gfortran, g95, ifort, pgf95, xlf95, sxf90, $\cdots$)
- **Source code**
  - **Stable version**: Web site (http://bpsi.nucleng.kyoto-u.ac.jp/task/)
  - **Latest version**: CVS tree (Read only) [password required]
  - **Developer**: CVS tree (R/W) [account required]
- **User support**
  - Uniform user interface
  - English guidebook in preparation: by the end of 2006