Korea-Japan Workshop on
Theory and Simulation of Magnetic Fusion Plasmas
KAIST Daejeon, 2006/08/16

Integrated Modeling of Tokamak Plasmas by TASK Code

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- TASK: Core Code for Integrated Modeling
- Summary

First Korea-Japan Fusion Theory Workshop

- **Japan-Korea Collaboration Program for Fusion Research**
  - Started in **2005**
  - **Category**
    - KSTAR/LHD/JT-60
    - Fusion Theory
    - Fusion Technology
    - Fusion Plasma (except theory and technology)
- **Fusion Theory**
  - Key Persons (Korea, Japan: Fukuyama)
  - Workshop/Conference, Personal exchange
  - **Japan $\rightarrow$ Korea**: one WS and a few PX per year expected
  - **Korea $\rightarrow$ Japan**: ?

Burning Plasma Simulation

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

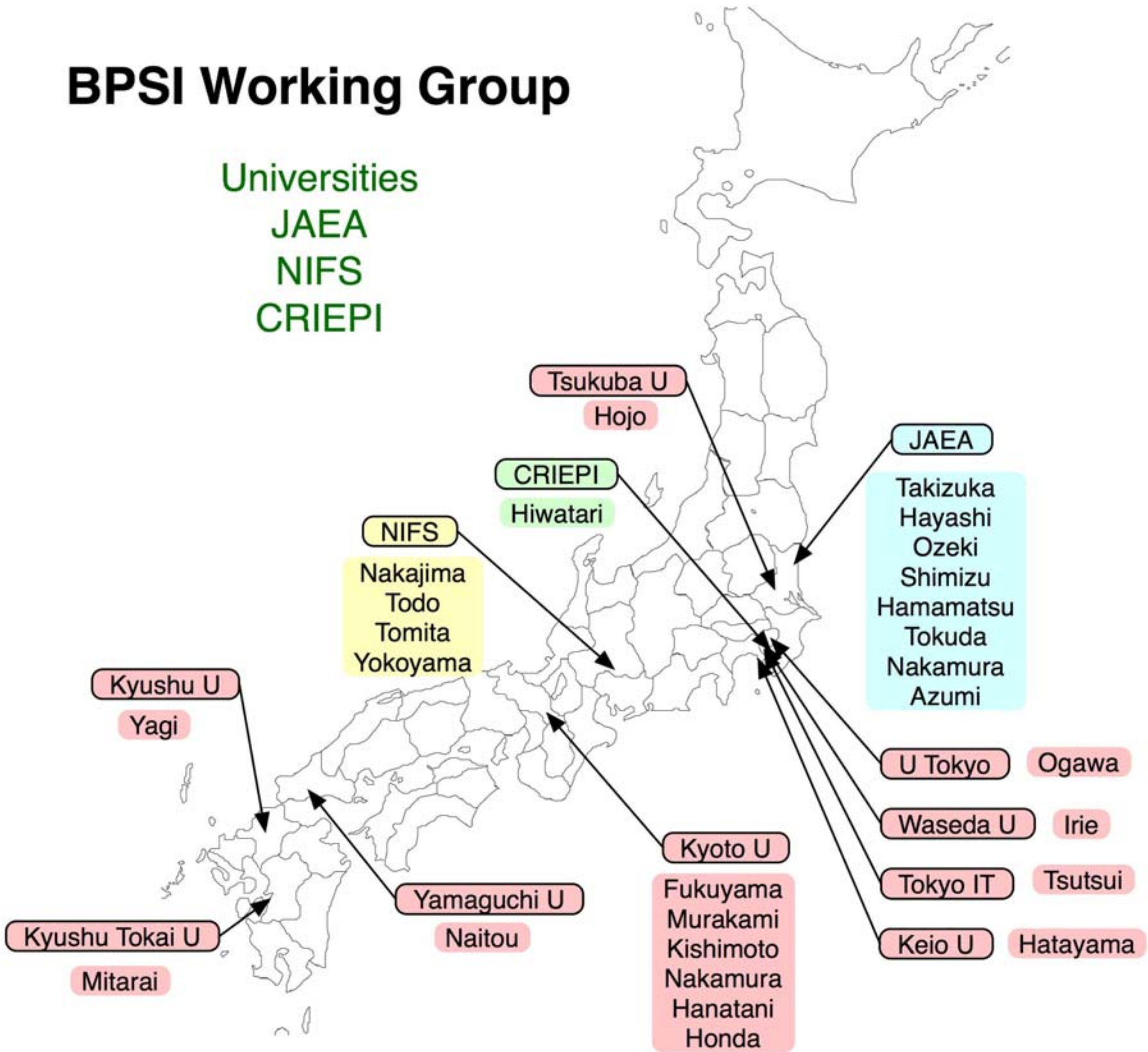
- **What is needed?**
  - **Simulation describing a burning plasma:**
    - **Whole plasma** (core & edge & divertor & wall-plasma)
    - **Whole discharge**
      (startup & sustainment & transients events & termination)
    - **Reasonable accuracy** (validation with experimental data)
    - **Reasonable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

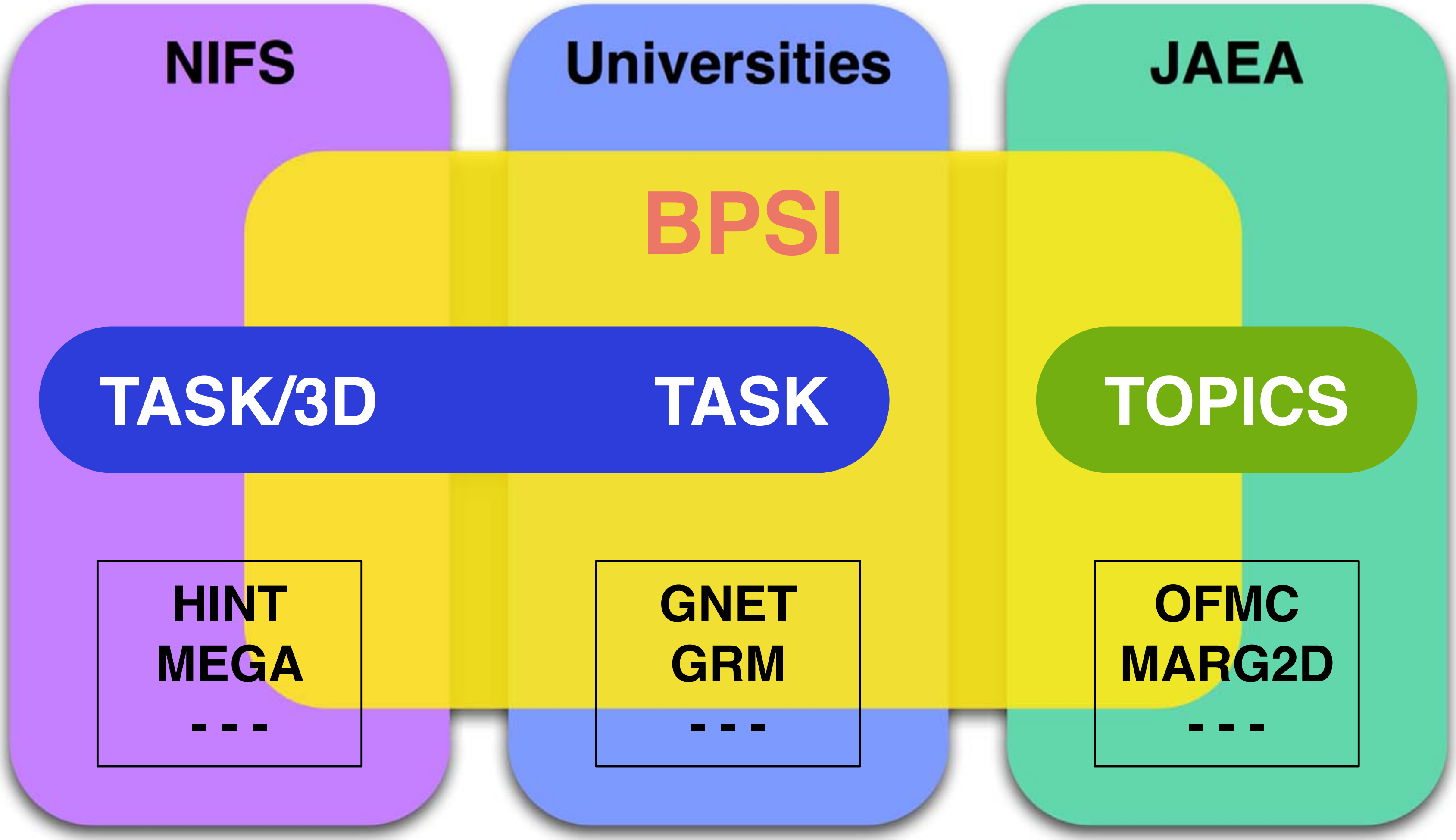


Targets of BPSI

- **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

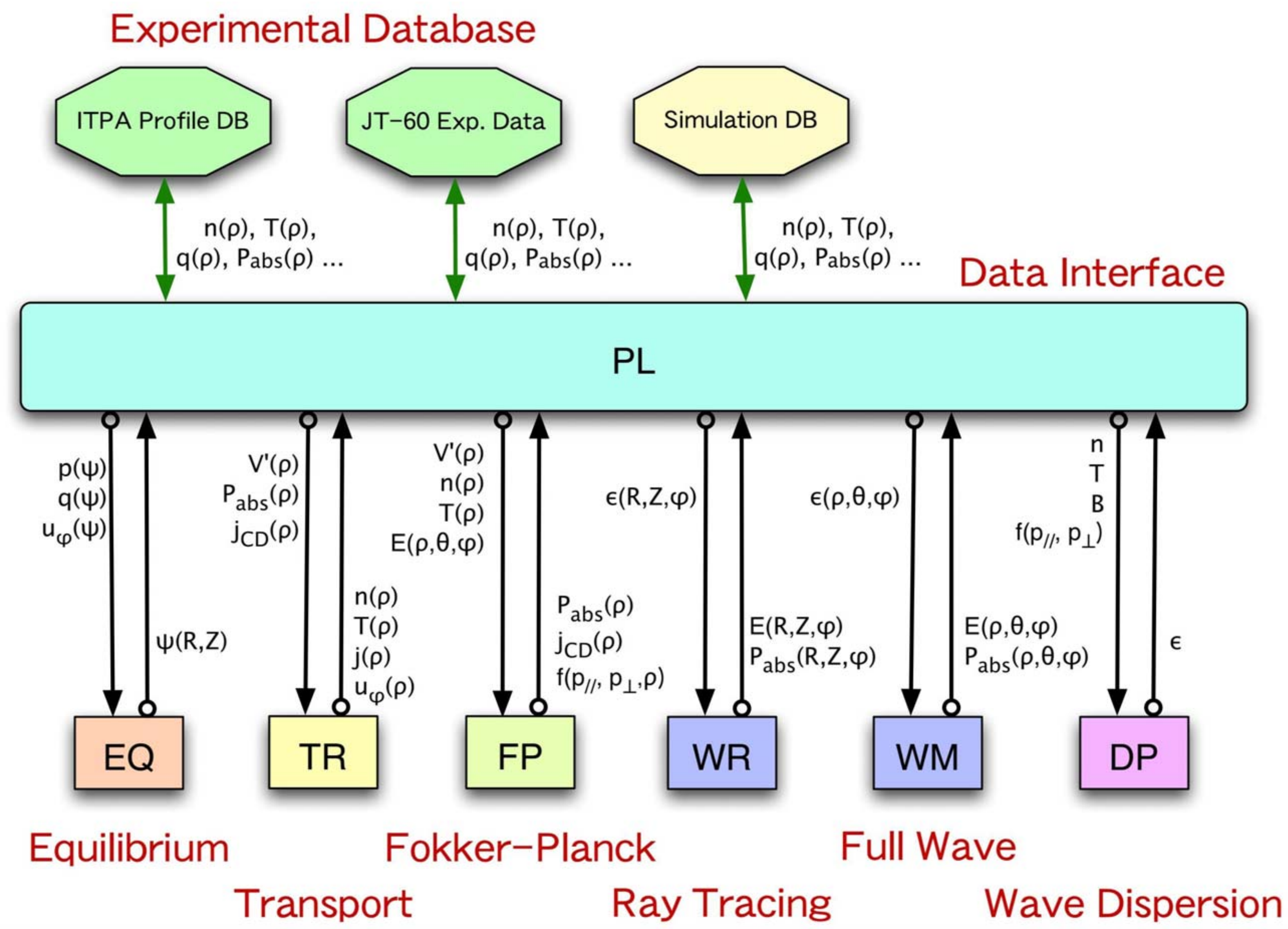
EQ	**2D Equilibrium**	Fixed/Free boundary, Toroidal rotation
TR	**1D Transport**	Diffusive transport, Transport models
WR	**3D Geometr. Optics**	EC, LH: Ray tracing, Beam tracing
WM	**3D Full Wave**	IC, AW: Antenna excitation, Eigen mode
FP	**3D Fokker-Planck**	Relativistic, Bounce-averaged
DP	**Wave 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)
```

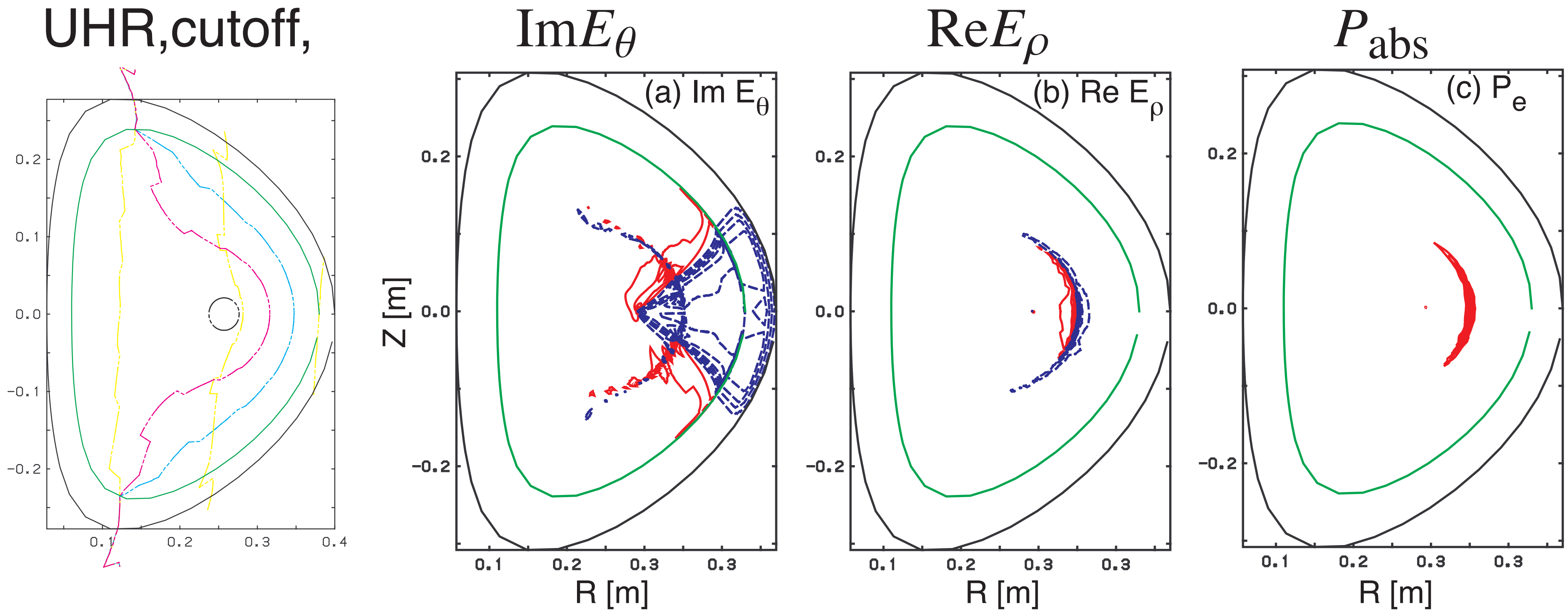
Recent Results of TASK code

EQ/WM	Full Wave Analysis of ECH in a Small-Size ST
WM/FP/DP	Development of Self-Consistent Wave Analysis
EQ/TR	Transport Simulation for ITER
EQ/TR/MW/DP	Integrated Analysis of AE in ITER Plasma
WA	Full Wave Analysis of RWM

Full Wave Analysis of ECH in a Small-Size ST

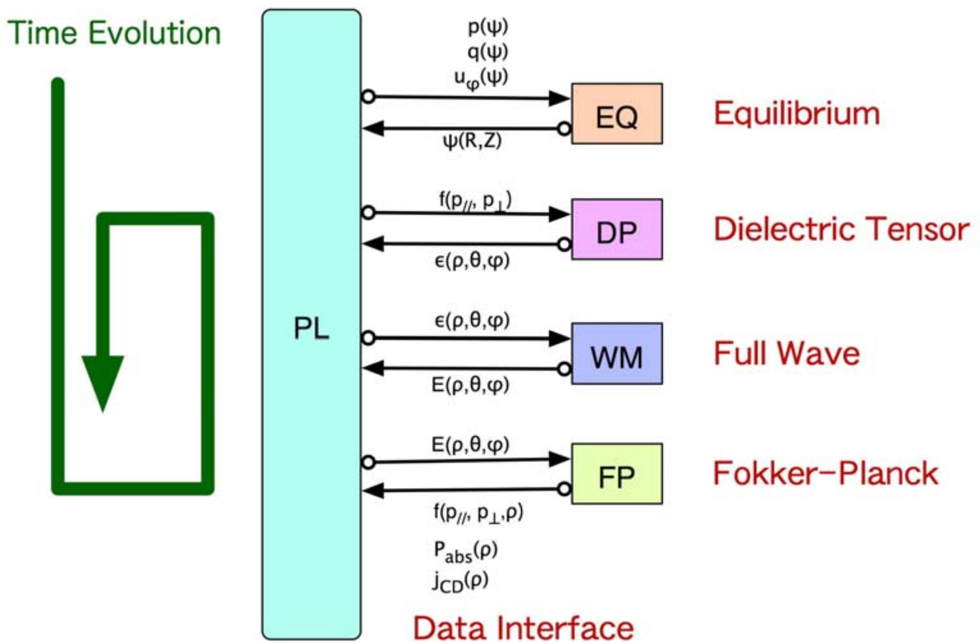
- **Small-size spherical tokamak: LATE** (Kyoto University)
  - **T. Maekawa et al., IAEA-CN-116/EX/P4-27 (Vilamoura, Portuga, 2004)**
  - $R = 0.22\,\mathrm{m}$, $a = 0.16\,\mathrm{m}$, $B_0 = 0.0552\,\mathrm{T}$, $I_p = 6.25\,\mathrm{kA}$, $\kappa = 1.5$
  - $f = 2.8\,\mathrm{GHz}$, Toroidal mode number $n = 12$, Extraordinary mode

Penetration through cutoff layer	$\Longrightarrow$	Propagation along the UHR layer	$\Longrightarrow$	Collisional damping near the UHR layer



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 $f(v)$**

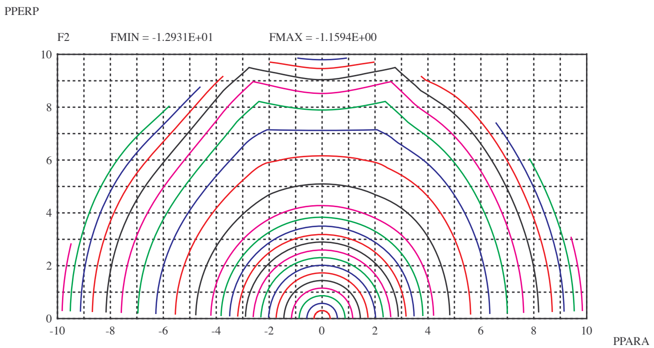


Development of Self-Consistent Wave Analysis

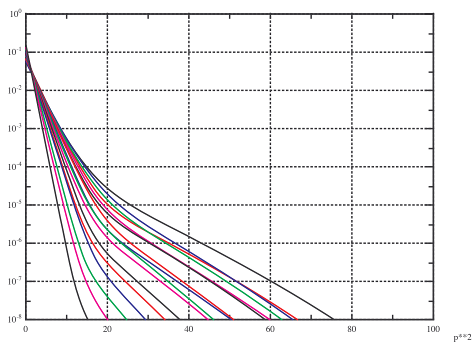
- **Code Development in TASK**
  - Ray tracing analysis with arbitrary $f(v)$: **Already done**
  - Full wave analysis with arbitrary $f(v)$: **Completed**
  - Fokker-Plank analysis of ray tracing results: **Already done**
  - Fokker-Plank analysis of full wave results: **Almost competed**
  - Self-consistent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

- **Tail formation by ICRF minority heating**

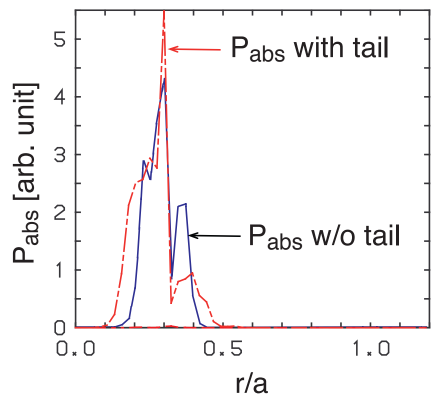
Momentum Distribution



Tail Formation



Power deposition



CDBM Transport Model: CDBM05

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

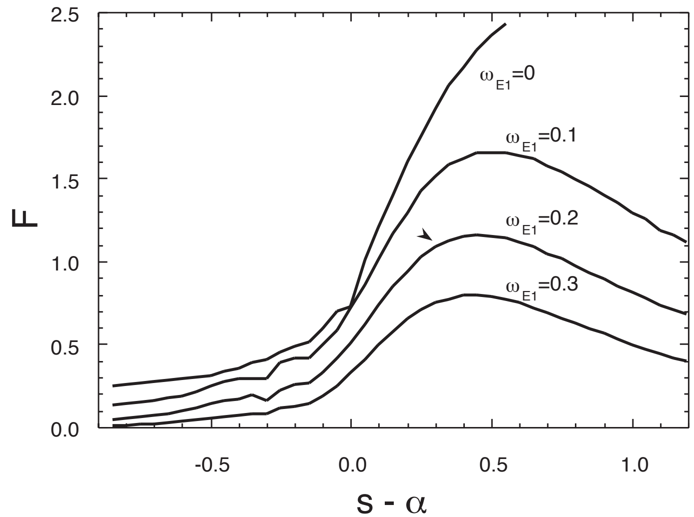
$$\chi_{\mathrm{TB}} = F(s, \alpha, \kappa, \omega_{\mathrm{E1}})\, \alpha^{3/2} \frac{c^2}{\omega_{\mathrm{pe}}^2} \frac{v_{\mathrm{A}}}{qR}$$

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

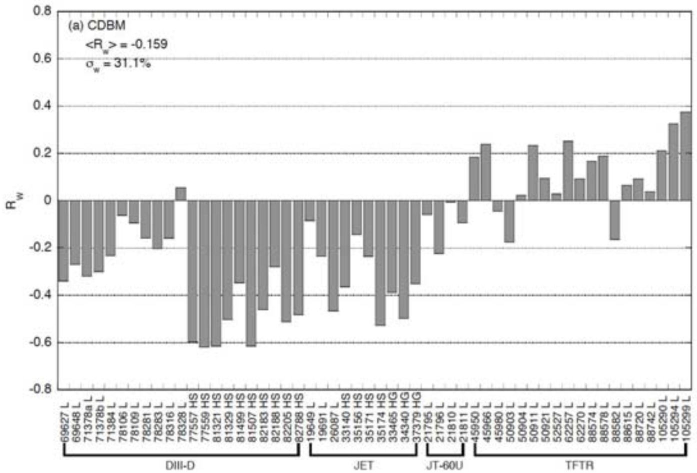


$$F(s, \alpha, \kappa, \omega_{\mathrm{E1}}) = \left(\frac{2\kappa^{1/2}}{1+\kappa^2}\right)^{3/2} \times \begin{cases} \dfrac{1}{1+G_1\omega_{\mathrm{E1}}^2} \dfrac{1}{\sqrt{2(1-2s')(1-2s'+3s'^2)}} & \text{for} \quad s' = s - \alpha < 0 \\[2ex] \dfrac{1}{1+G_1\omega_{\mathrm{E1}}^2} \dfrac{1+9\sqrt{2}s'^{5/2}}{\sqrt{2}(1-2s'+3s'^2+2s'^3)}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

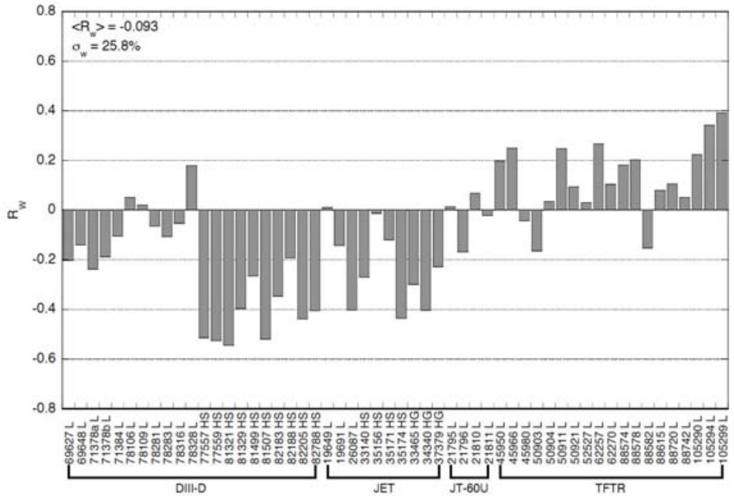
Comparison of Transport Models: ITPA Profile DB

Deviation of Stored Energy

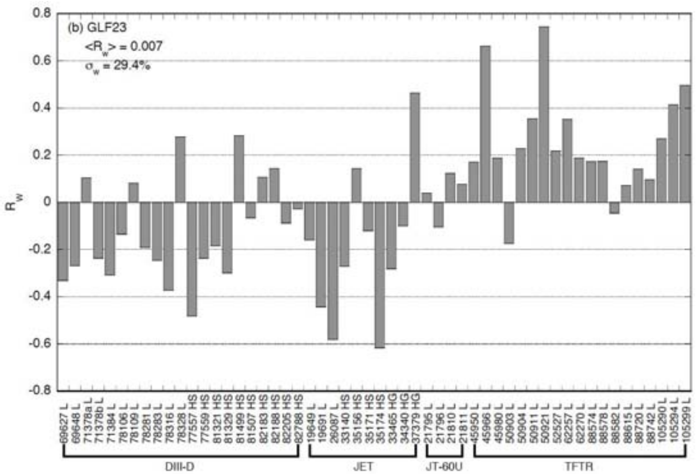
CDBM



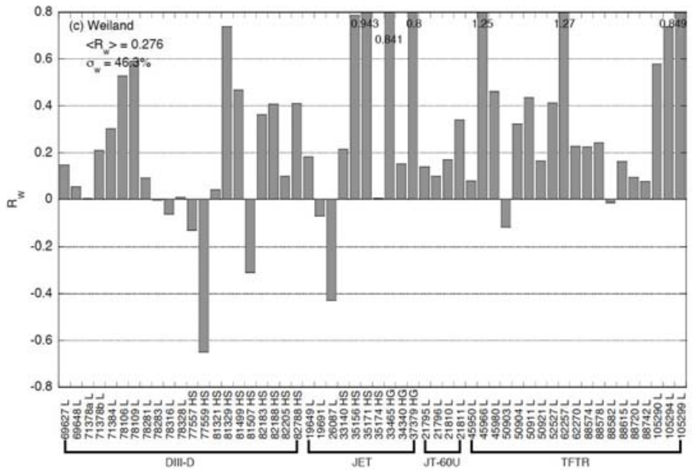
CDBM05



GLF23

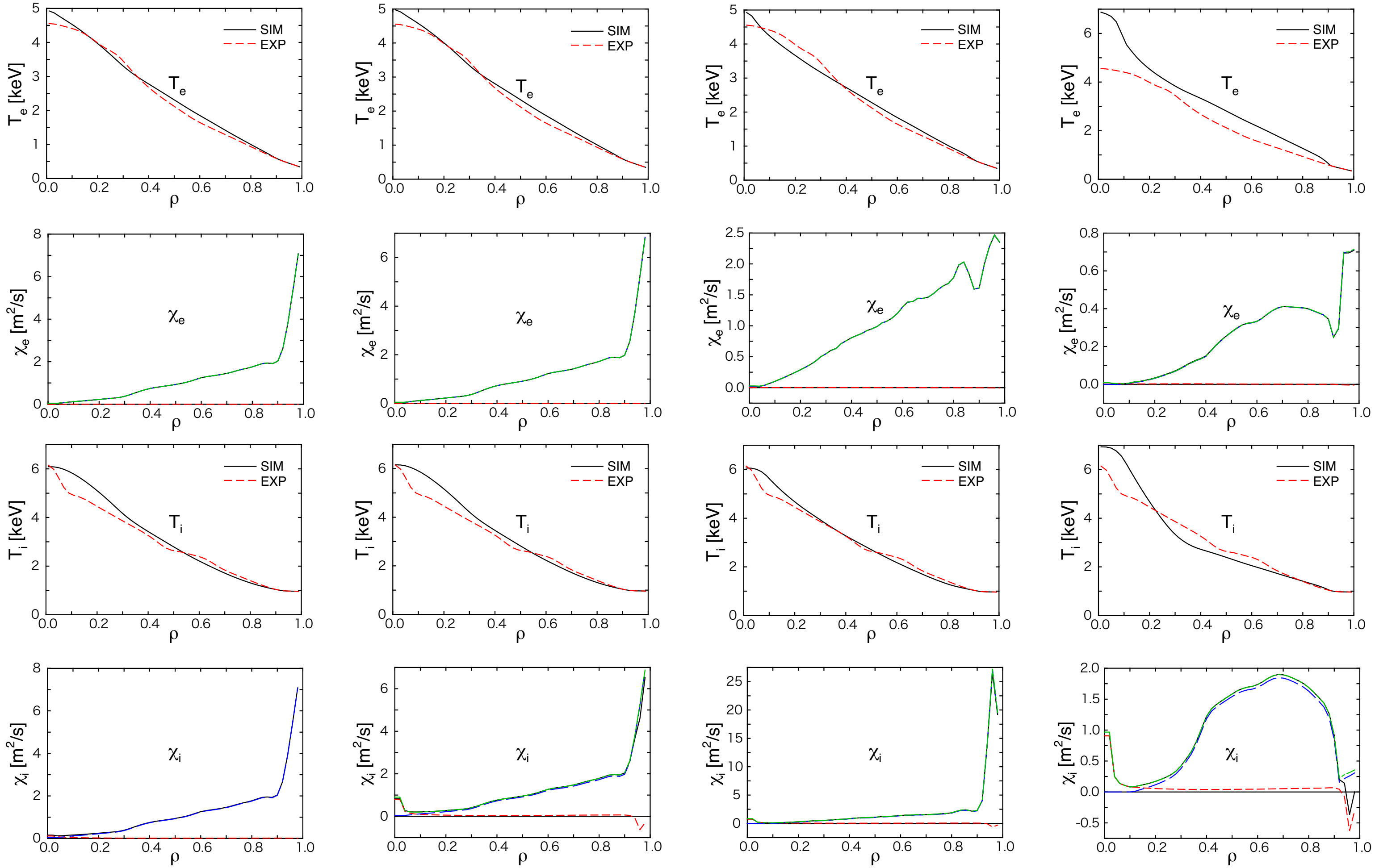


Weiland

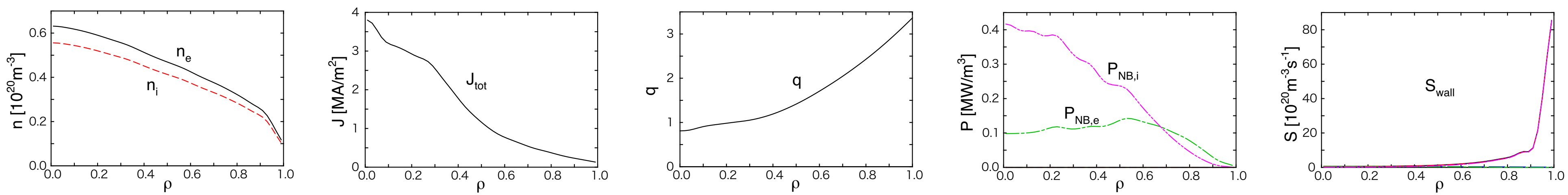


TFTR #88615 (L-mode, NBI heating)

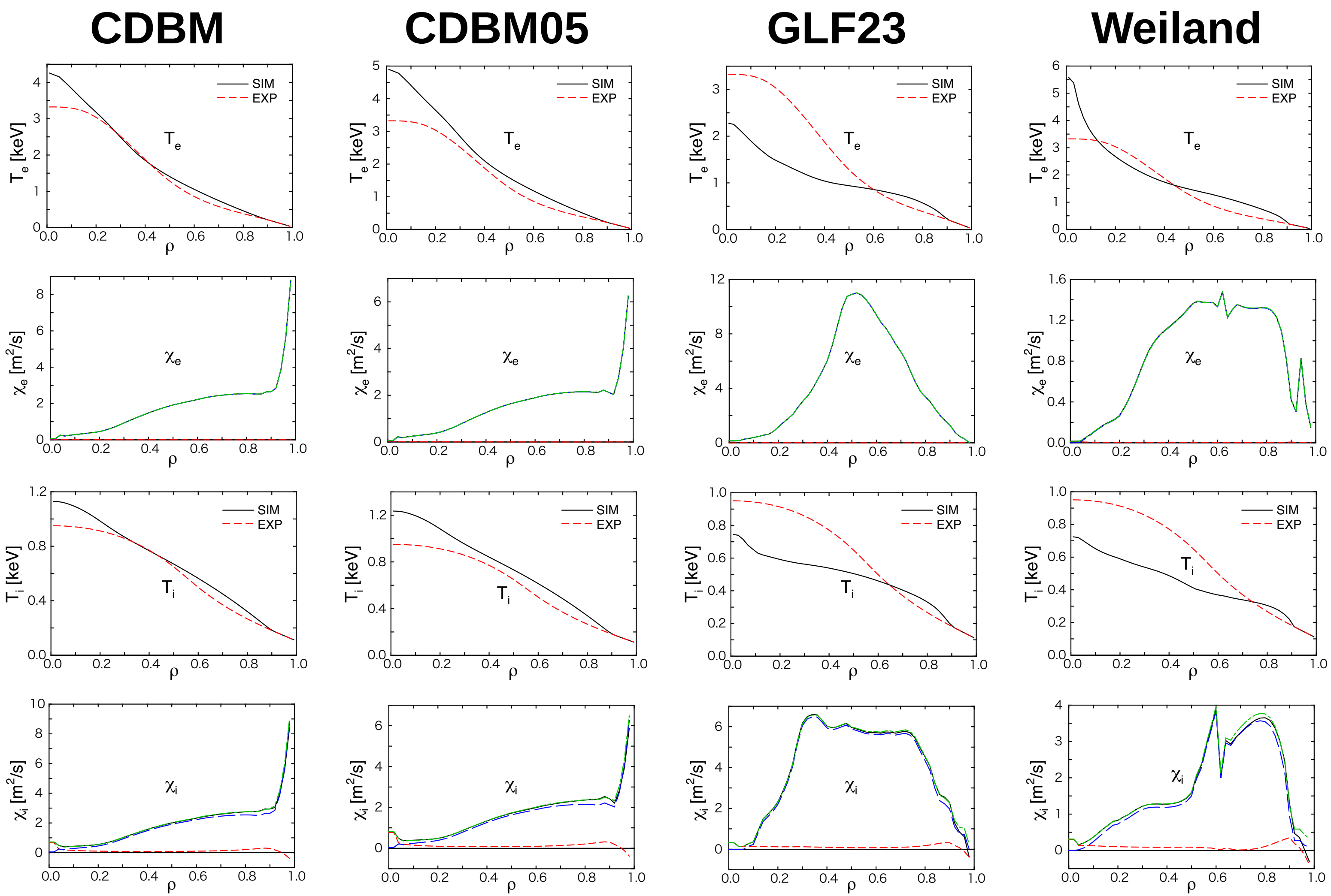
CDBM CDBM05 GLF23 Weiland



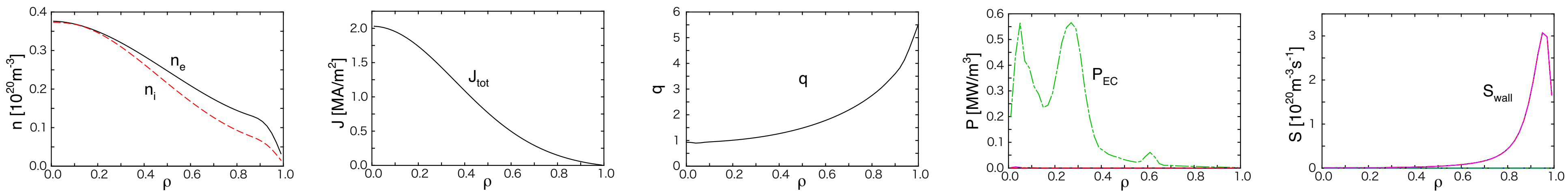
Common Profiles



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



Common Profiles



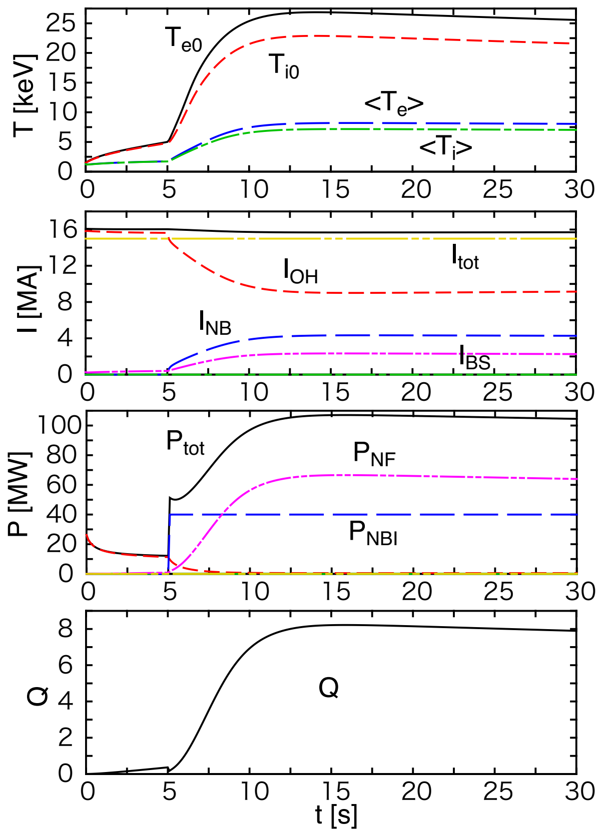
High Q Operational Scenario

- Large plasma current: $I_\mathrm{p} = 15$ MA, On-axis heating: $P_\mathrm{NB} = 40$ MW
- Positive shear profile, Relatively large f_OH

CDBM

$\beta_\mathrm{N} = 1.49$

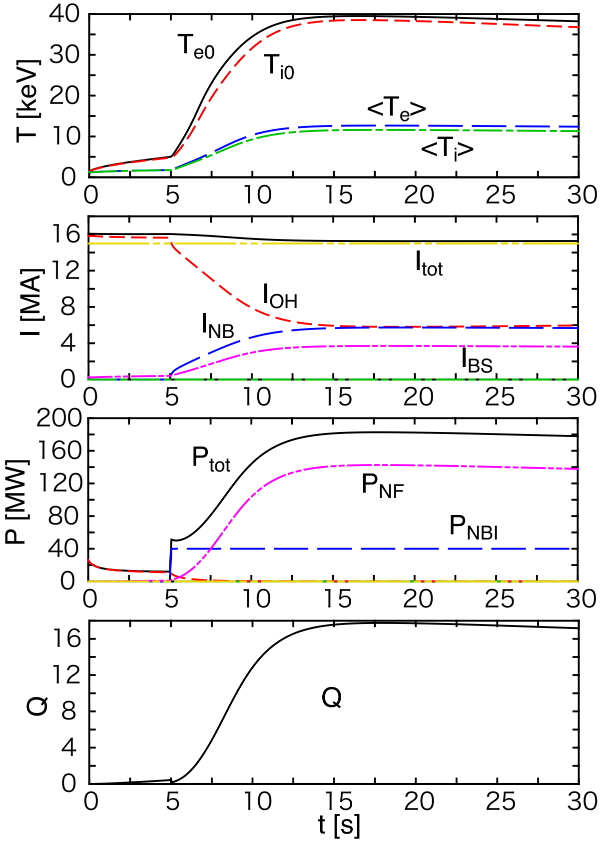
$\tau_\mathrm{E} = 3.0$ s

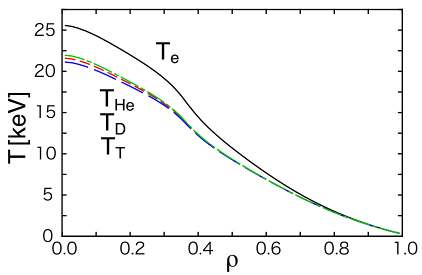


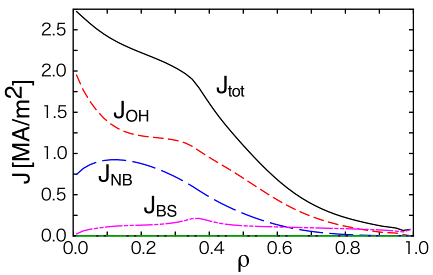
CDBM05

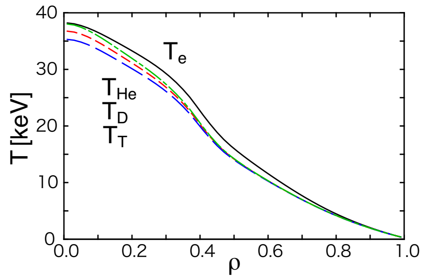
$\beta_\mathrm{N} = 2.63$

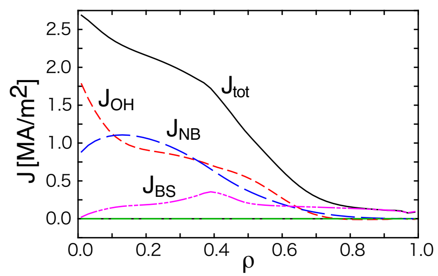
$\tau_\mathrm{E} = 3.1$ s











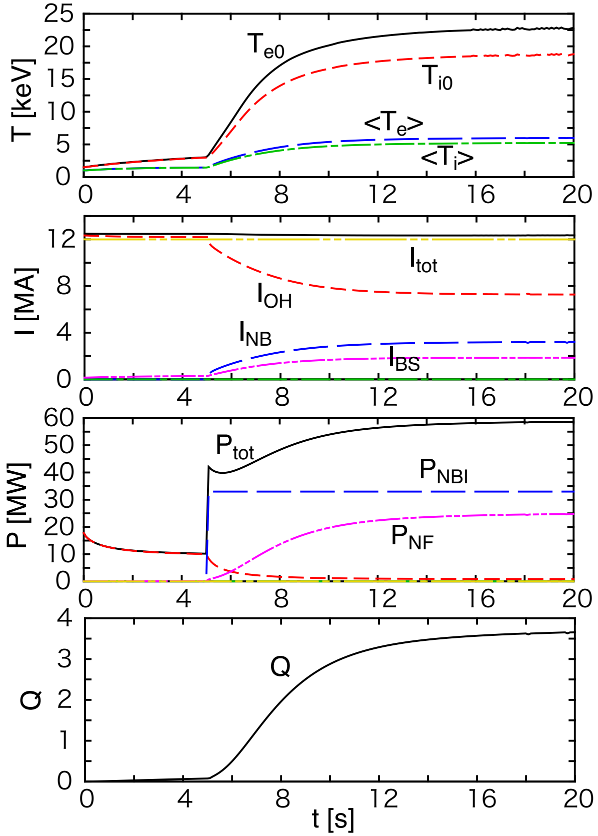
Hybrid Operational Scenario

- 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

$\beta_{\mathrm{N}} = 1.17$

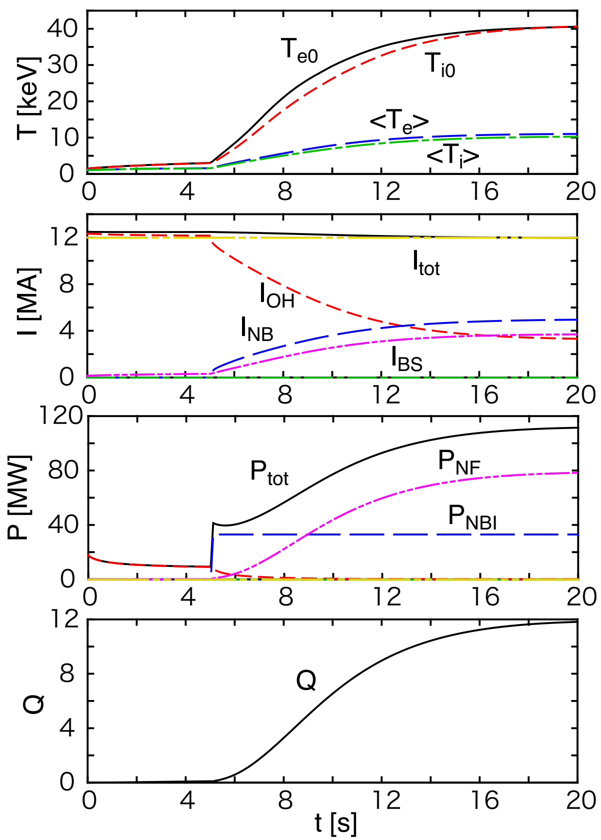
$\tau_{\mathrm{E}} = 3.1$ s

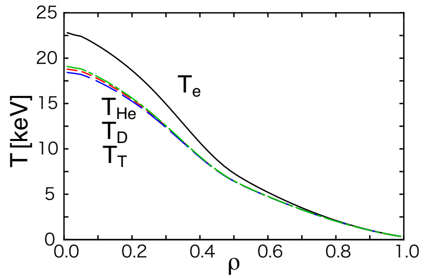


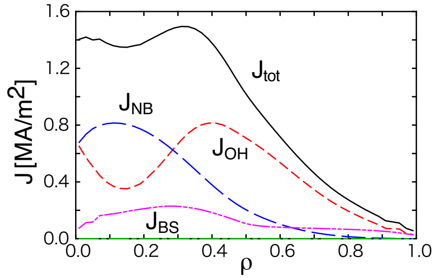
CDBM05

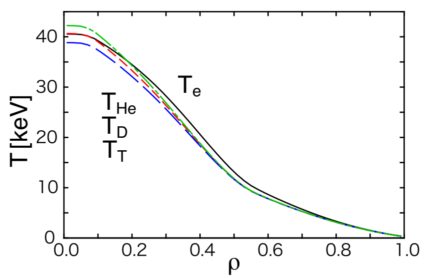
$\beta_{\mathrm{N}} = 2.58$

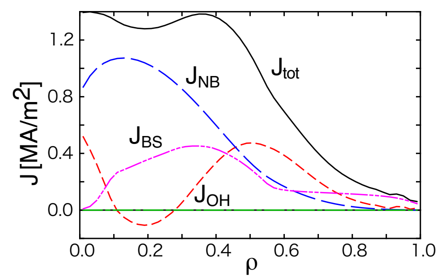
$\tau_{\mathrm{E}} = 3.6$ s











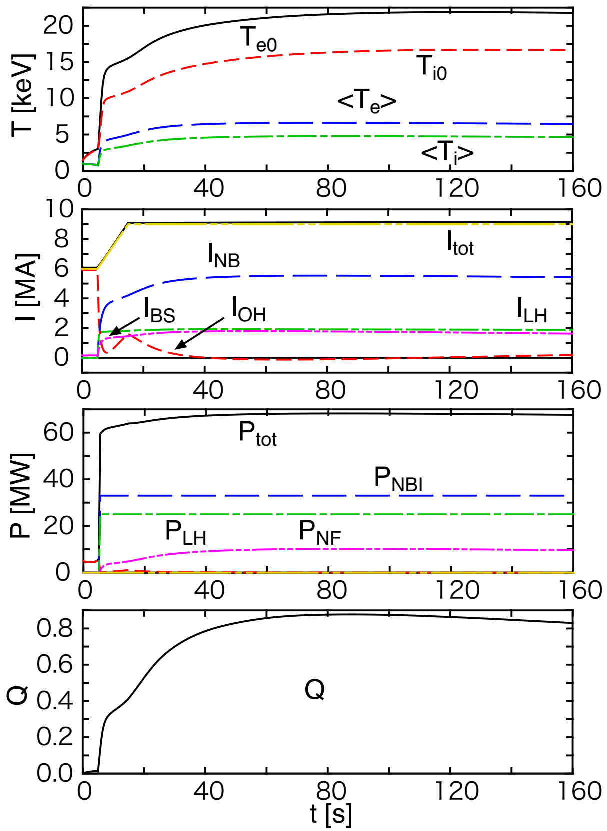
Quasi-Steady State Operational Scenario

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

CDBM

$\beta_N = 1.2$

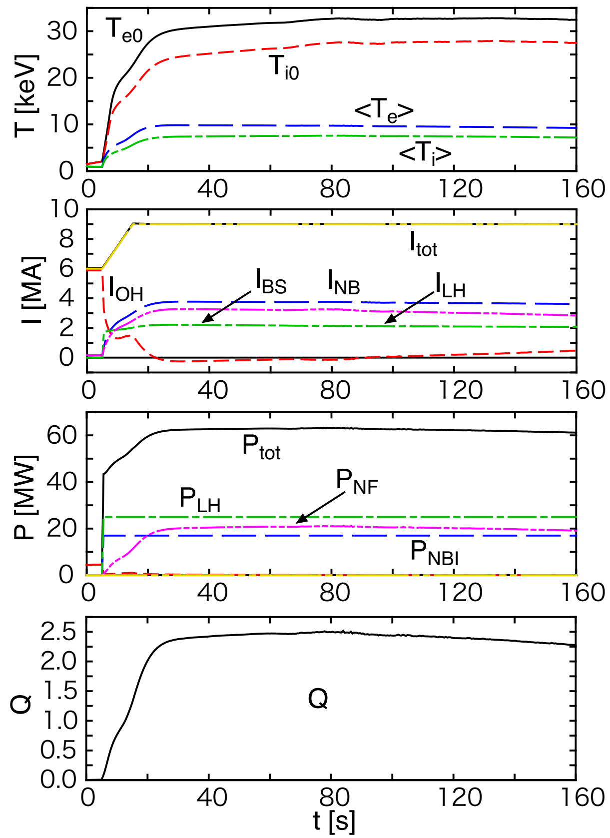
$\tau_E = 3.0$ s

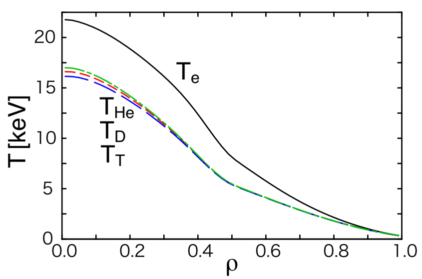


CDBM05

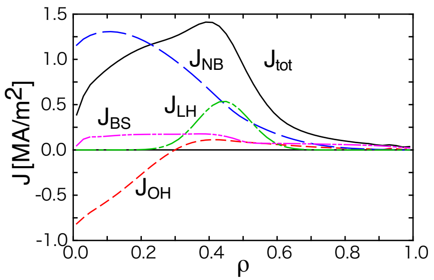
$\beta_N = 1.55$

$\tau_E = 3.2$ s

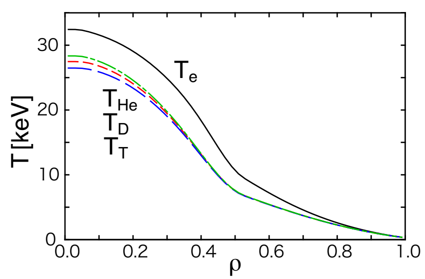




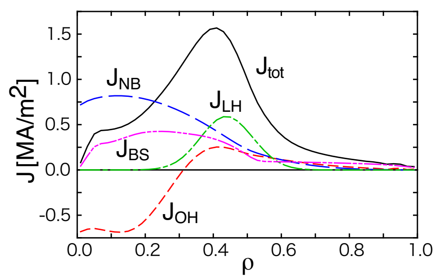
P_{NB} = 35 MW



P_{LH} = 30 MW

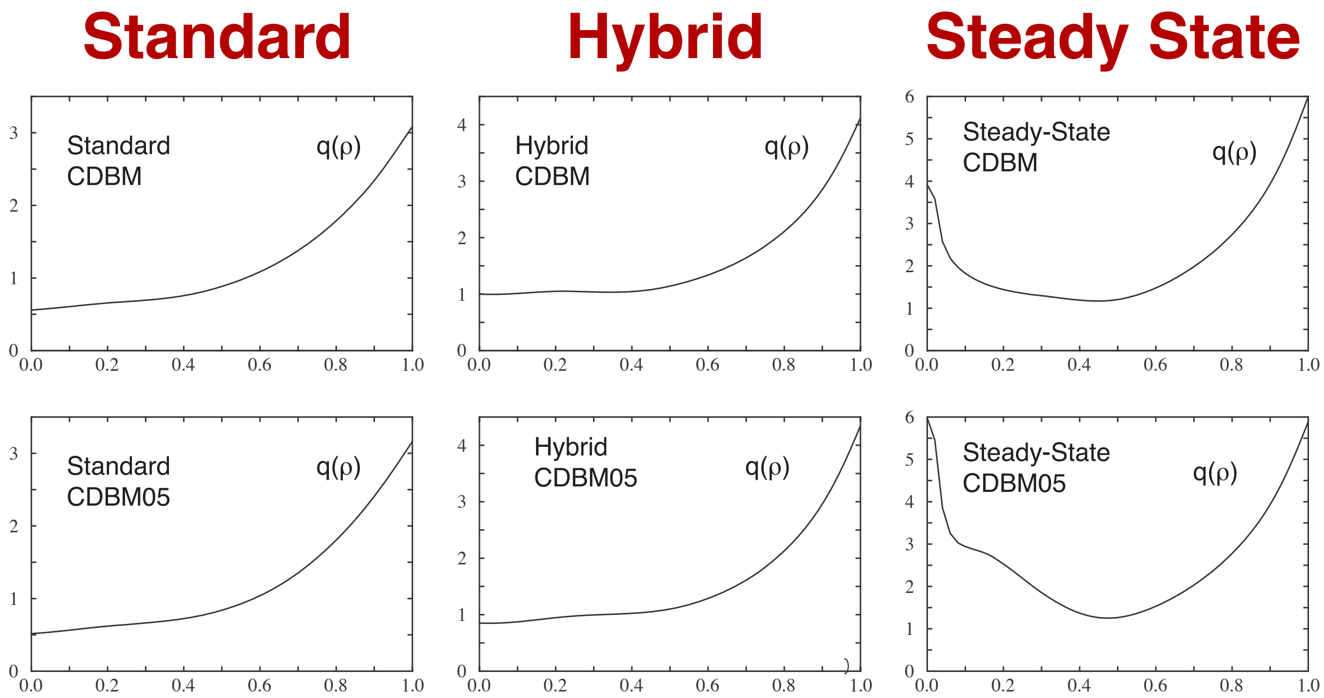


P_{NB} = 17 MW



P_{LH} = 25 MW

q Profiles of Previous Shots



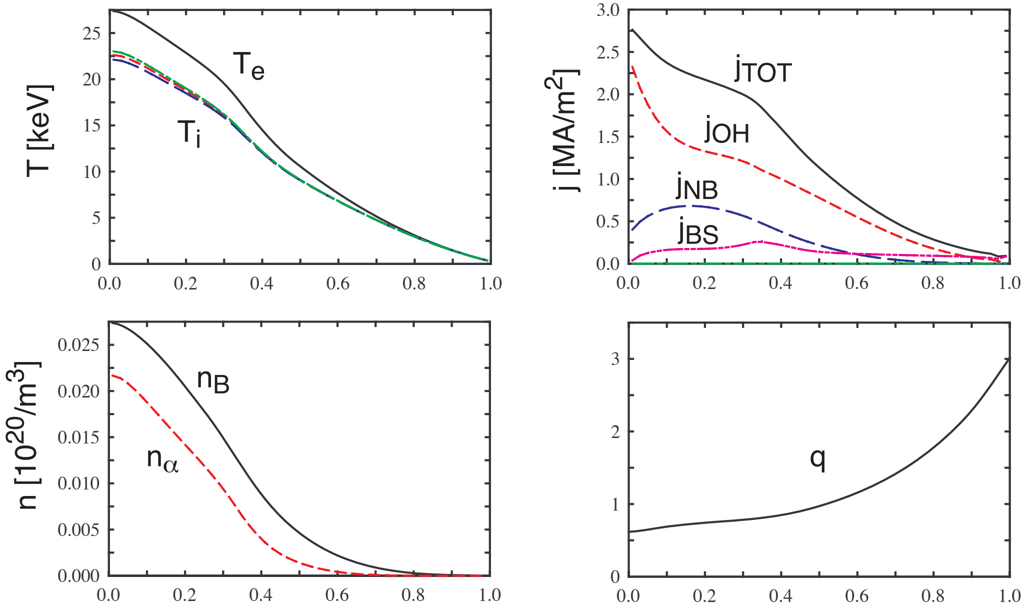
- Control of current profile in the hybrid operation requires more improvement to keep $q(0) > 1$.
- Performance of the quasi steady-state operation will be improved if the H-mode plasma edge (edge transport barrier) are included. .

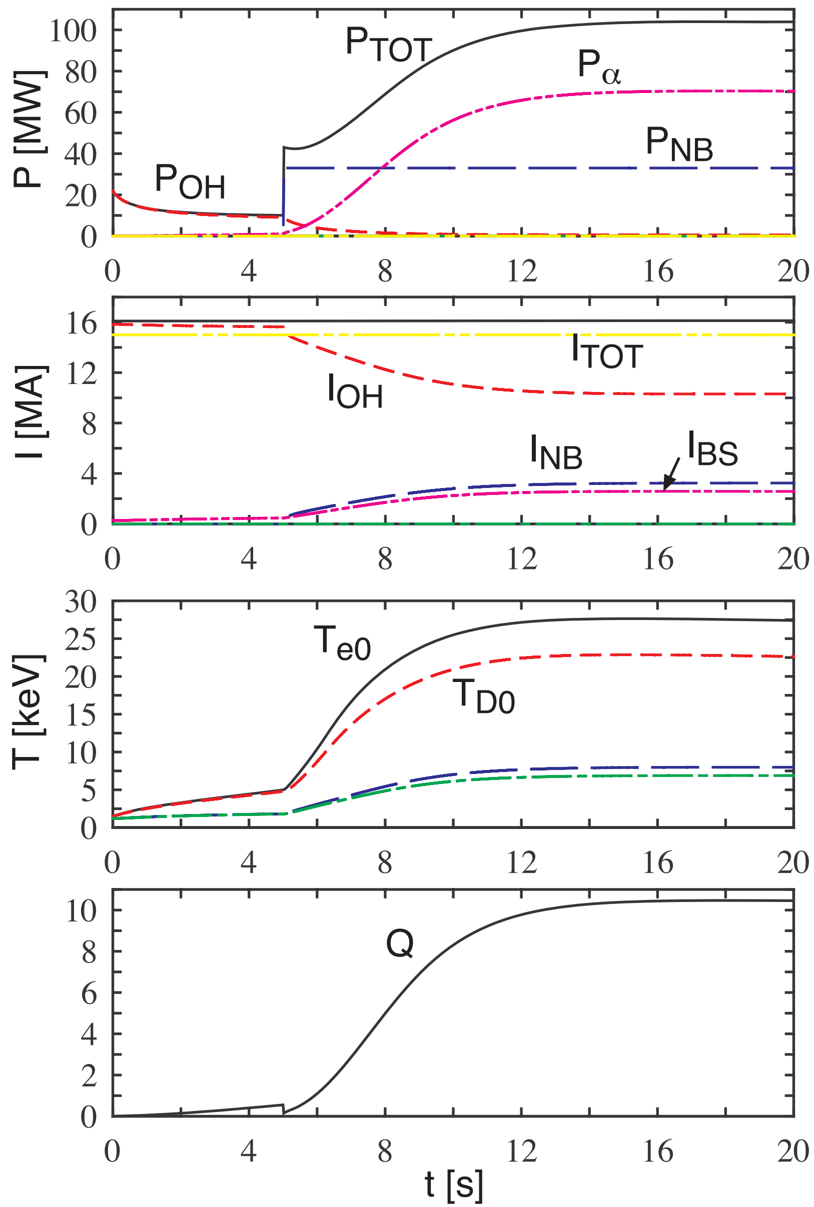
Integrated Analysis of AE in ITER Plasma

- **Combined Analysis**
  - **Equilibrium**: TASK/EQ
  - **Transport**: TASK/TR
    - Turbulent transport model: CDBM
    - Neoclassical transport model: NCLASS (**Houlberg**)
    - Heating and current profile: given profile
  - **Full wave analysis**: TASK/WM
- **Stability analysis**
  - Standard H-mode operation: $I_{\rm p} = 15\,{\rm MA}$, $Q \sim 10$
  - Hybrid operation: $I_{\rm p} = 12\,{\rm MA}$, flat q profile above 1
  - Steady-state operation: $I_{\rm p} = 9\,{\rm MA}$, reversed shear

Standard H-mode Operation

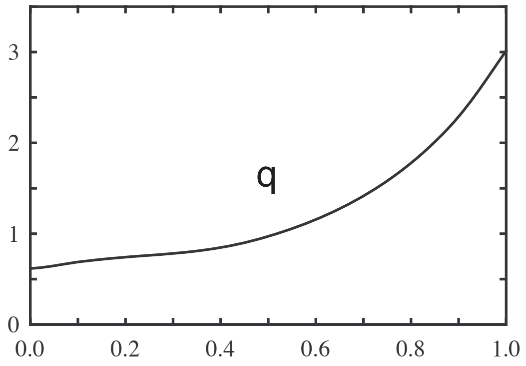
- $I_p = 15\,\mathrm{MA}$
- $P_{NB} = 33\,\mathrm{MW}$
- $\beta_N = 1.3$



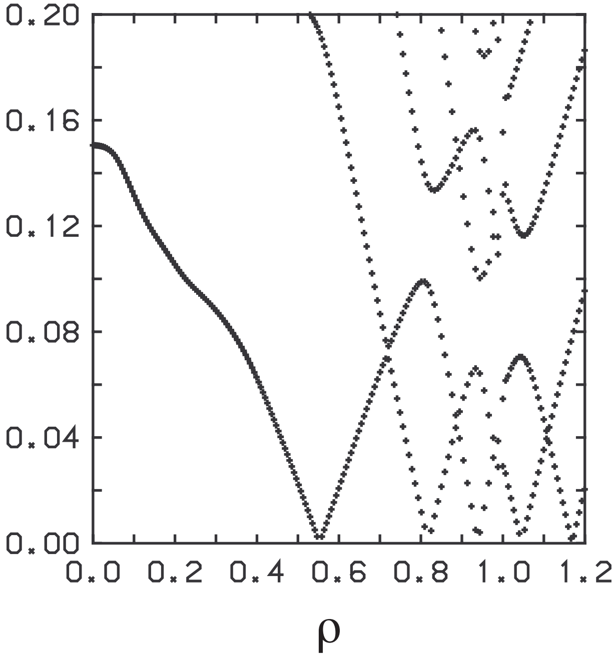


AE in Standard H-mode Operation

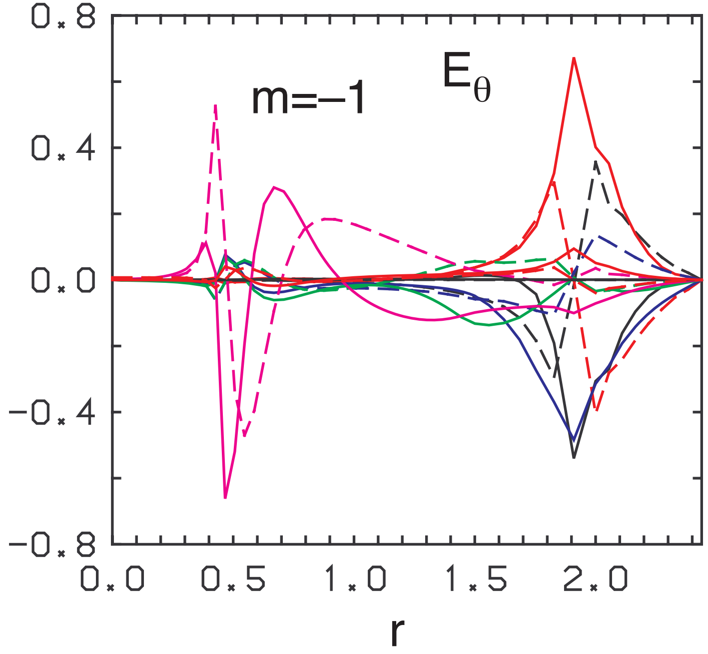
q profile



Alfvén Continuum



Mode structure ($n = 1$)



$f_r = 95.95\,\mathrm{kHz}$

$f_i = -1.95\,\mathrm{kHz}$

Stabilization due to $q = 1$

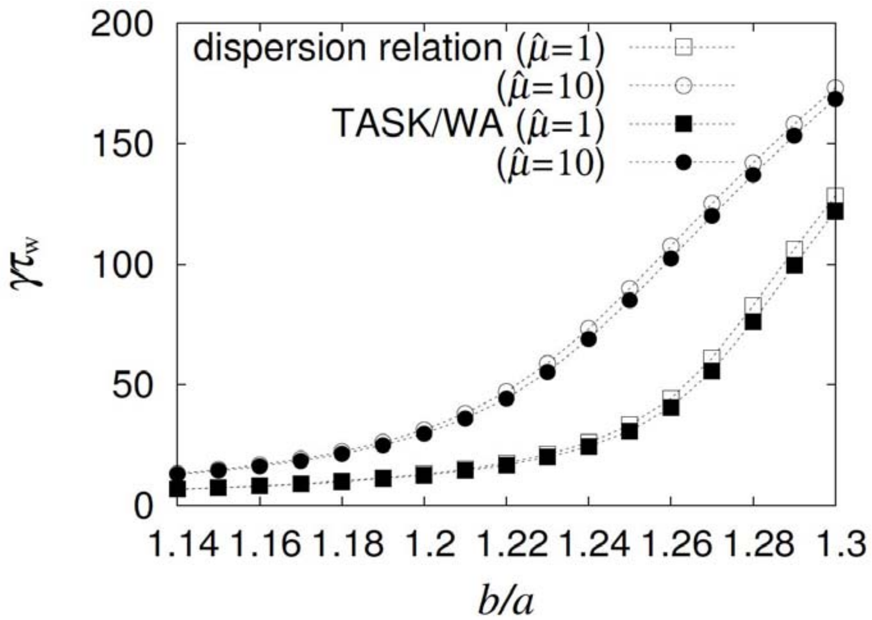
Full Wave Analysis of RWM (TASK/WA)

- **Full wave analysis**: solving Maxwell's eqation

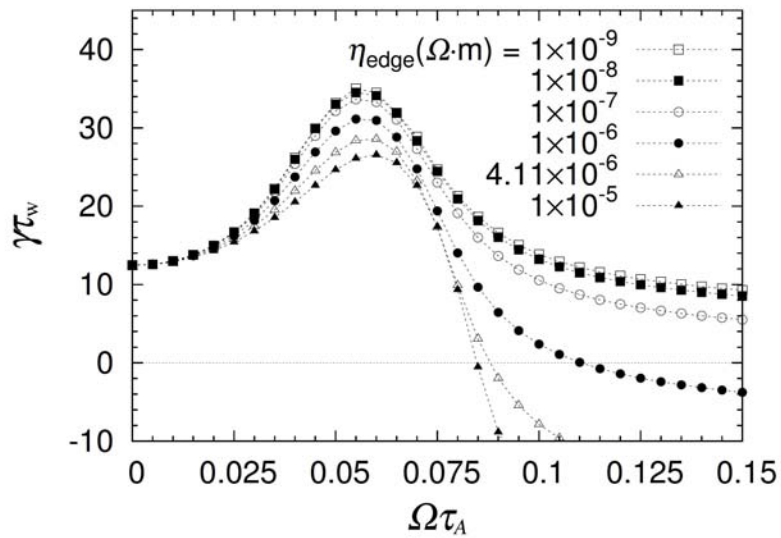
$$\nabla \times \nabla \times \boldsymbol{E} = \frac{\omega^2}{c^2} \overleftrightarrow{\epsilon} \cdot \boldsymbol{E} + \mathrm{i}\,\omega\mu_0 \boldsymbol{j}_{\mathrm{ext}}$$

- **Resistive MHD dielectric tensor including diamagnetic flow**
- **Ferromagnetic Resistive wall**

b/a dependence



Rotation dependence



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.
- **Standard dataset** and **module interface** will be implemented by the end of this summer.
- 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 NIFS.
- **Cooperation with TOPICS code** (developed in JAEA) has started.

Access to TASK code

- **Required Environment**
  - Unix-like OS (Linux, Mac OSX, · · ·)
  - X-window system
  - Fortran95 compiler (gfortran, g95, ifort, pgf95, xlf95, sxf90, · · ·)
- **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