ITPA CDBM TG
PPPL, 2006/04/26

Japanese Efforts on the Integrated Modeling
Part I
BPSI Activity and TASK Code Development

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Contents

- BPSI: Burning Plasma Simulation Initiative
- TASK: Core Code for Integrated Modeling
- Summary

Burning Plasma Simulation

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

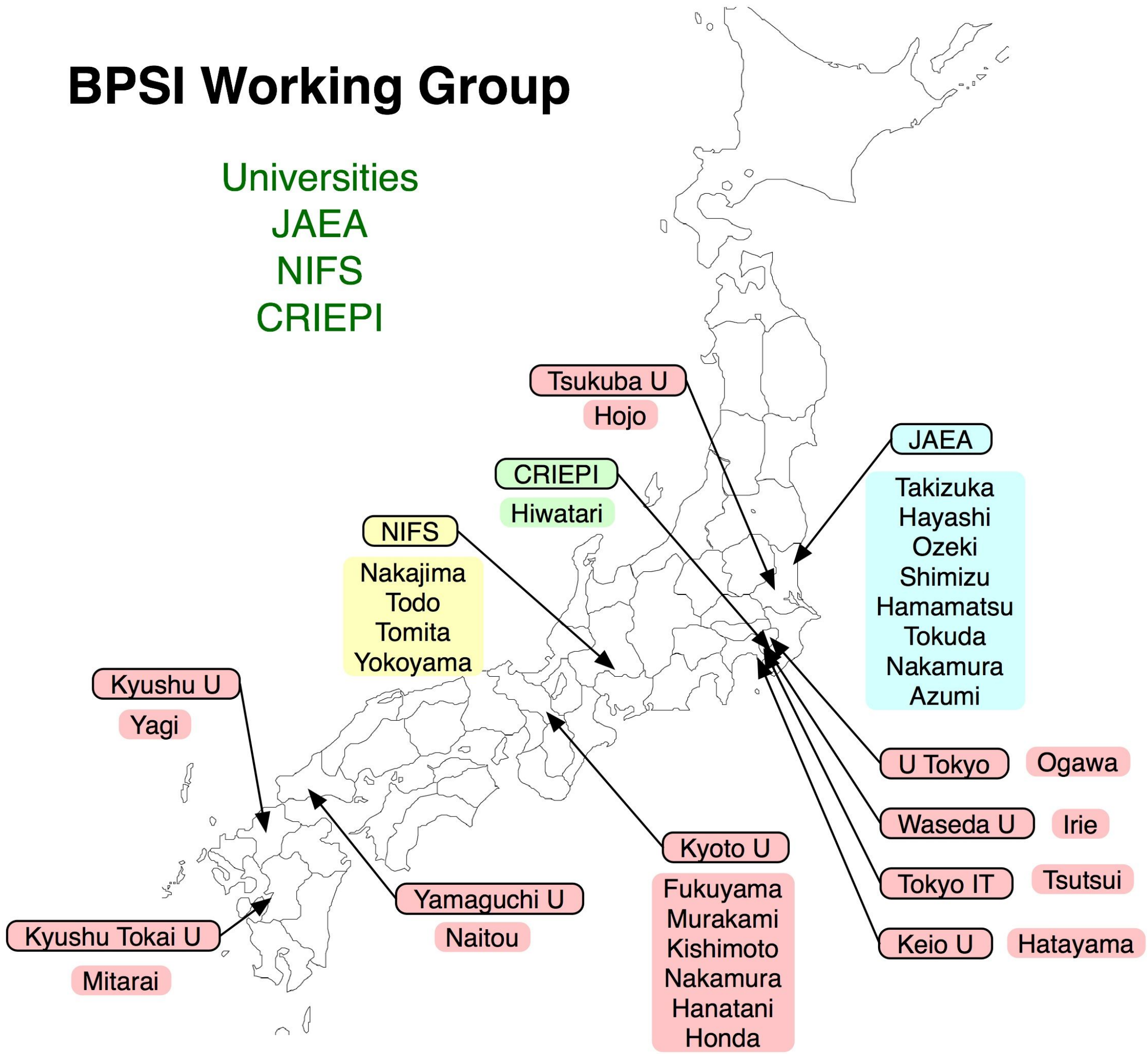
- **What is needed?**
  - **Simulation describing a burning plasma:**
    — **Whole plasma** (core & edge & divertor & wall-plasma)
    — **Whole discharge**
    (startup & sustainment & transients events & termination)
    — **Reasonable accuracy** (validation with experimental data)
    — **Reasonable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

Status of BPSI

- **1st Stage**:**present status**
  - **Development of standard dataset and module interface**
  - **Integrated simulation of multi-scale physics**
  - Validation of modules with **experimental results**
  - Transport simulation in **3D helical configuration**
- **2nd Stage**
  - **Integration of existing and newly-developed modules**
  - **Global integrated simulation** (Core+Edge, Transport+RF+MHD,. . .)
  - Validation of modules with **direct numerical simulation**
  - Integrated simulation in **3D helical configuration**
- **3rd Stage**
  - **Integrated simulation including startup and termination**
  - **Full integrated simulation of burning plasmas**

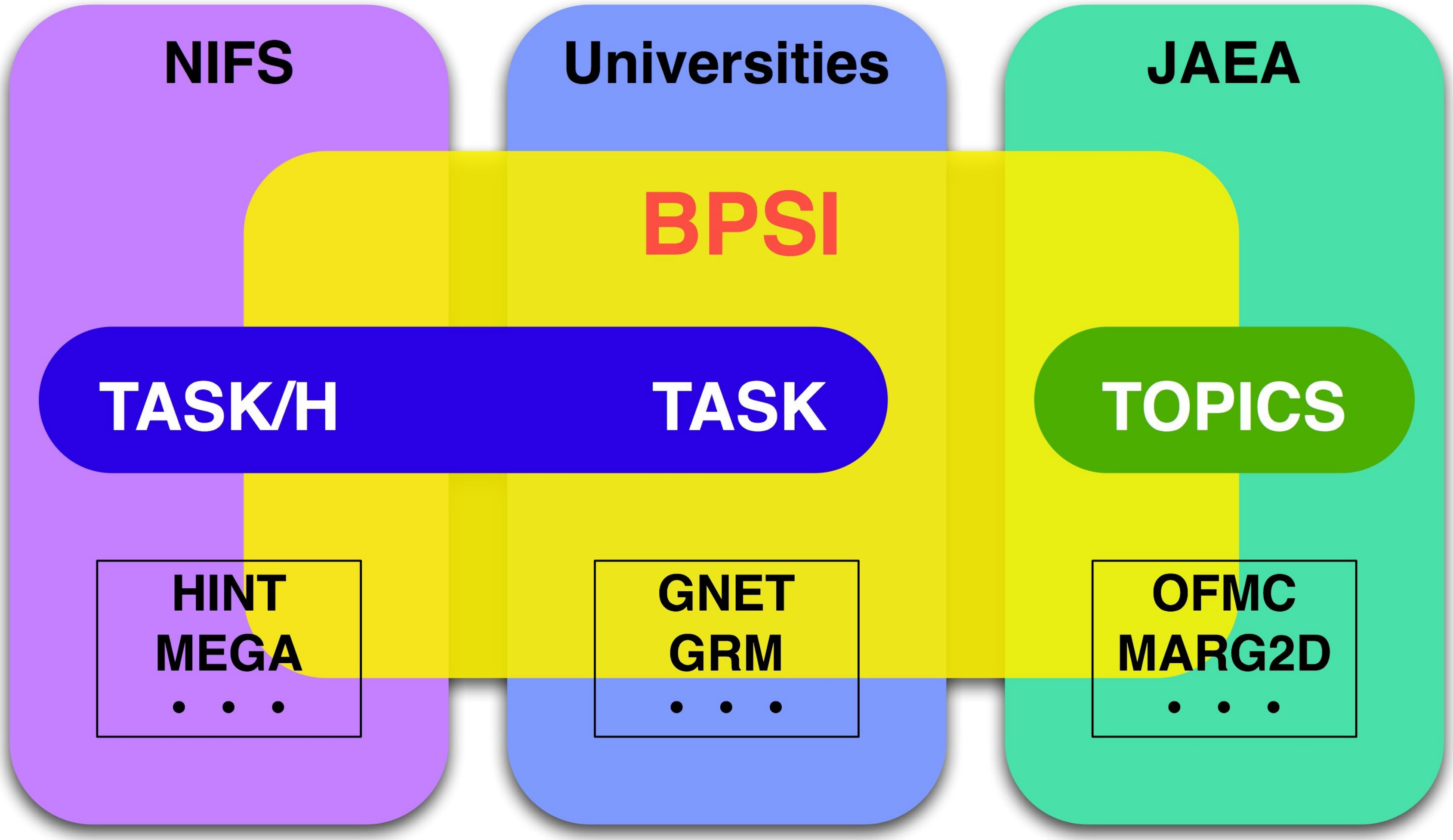
Activities of BPSI

- **Support of Meetings**
  - Domestic workshops (supported by RIAM, NIFS, JAEA)
  - Workshop with experimentalists (supported by NF Forum)
  - US-Japan workshop with participation from EU
  - Korea-Japan workshop

- **Code Development**
  - **BPSI Framework**: standard dataset and interface
    - **TASK code**: (Kyoto U)
    - **TASK/H for helical plasmas**: (NIFS, Kyoto U)
    - **Predictive TOPICS for burning plasmas**: (JAEA)
  - **Development of integrated modeling**:
    - Transport-Turbulence-MHD (Kyushu U)
    - Core-SOL-Divertor (JAEA, CRIEPI, Tokyo U)

BPSI: Burning Plasma Simulation Initiative

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

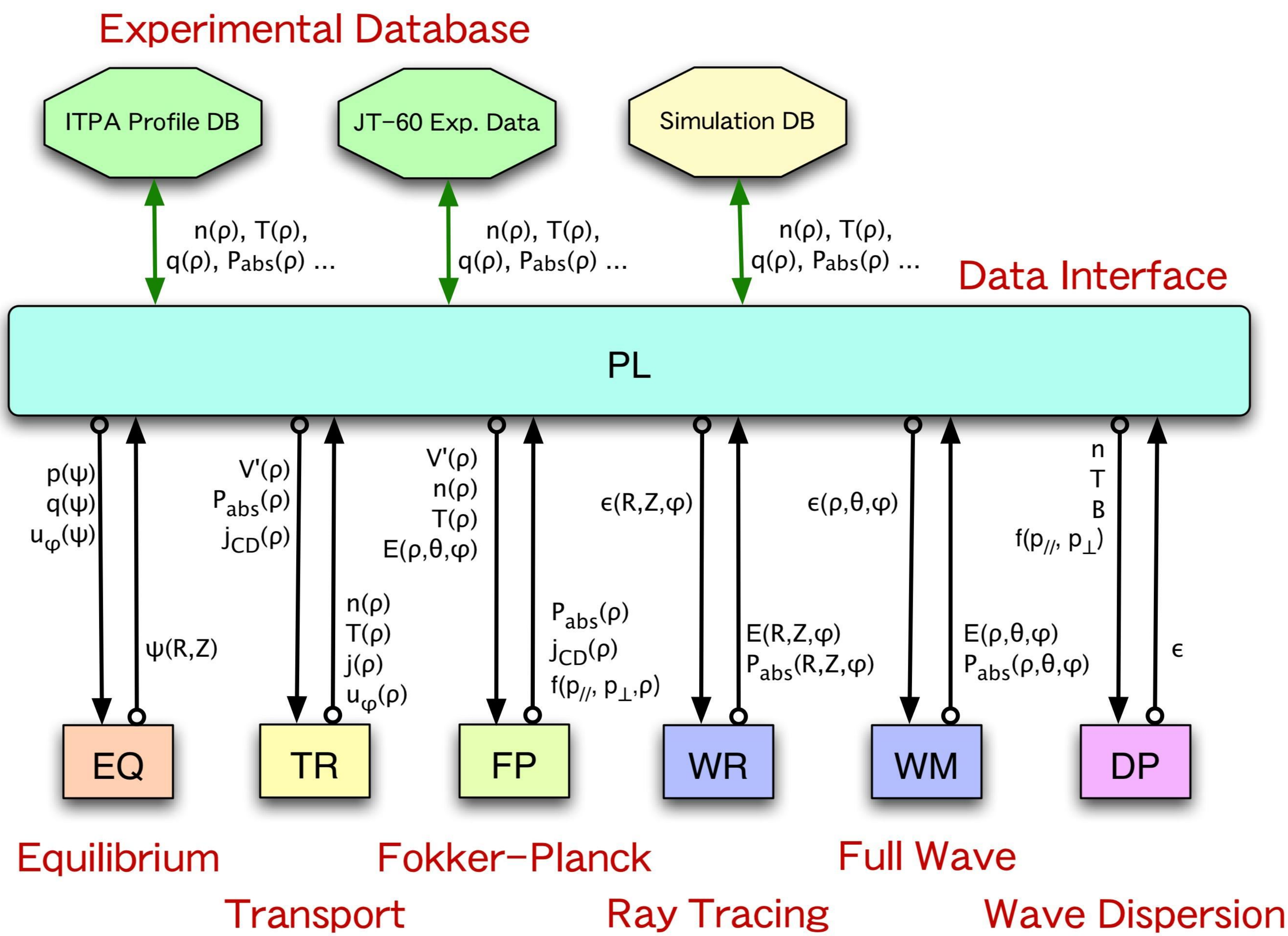
EQ	**2D Equilibrium**	Fixed/Free boundary, Toroidal rotation
TR	**1D Transport**	Diffusive transport, Transport models
WR	**3D Geometr. Optics**	EC, LH: Ray tracing, Beam tracing
WM	**3D Full Wave**	IC, AW: Antenna excitation, Eigen mode
FP	**3D Fokker-Planck**	Relativistic, Bounce-averaged
DP	**Wave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



Standard Dataset (interim 1/3)

- **Shot data**
  - Machine ID, Shot ID, Model ID
- **Device data**: (Level 1)

RR	R	m	Geometrical major radius
RA	a	m	Average minor radius $(R_{\mathrm{max}} - R_{\mathrm{min}})/2$
RB	b	m	Wall radius
BB	B	T	Vacuum toroidal magnetic field at $(RR, 0)$
RKAP	κ		Elongation of plasma boundary
RDLT	δ		Triangularity of plasma boundary
RIP	I_{p}	A	Typical plasma current

- **Equilibrium data**: (Level 1)

PSIP	$\psi_{\mathrm{p}}(R, Z)$	Tm^2	2D poloidal magnetic flux
PSIR	$\psi(\rho)$	Tm^2	Poloidal magnetic flux
PPSI	$p(\rho)$	MPa	Plasma pressure
TPSI	$T(\rho)$	Tm	$B_\phi R$
QPSI	$1/q(\rho)$		Safety factor
JPAV	$j_{\parallel}^{\mathrm{ave}}(\rho)$		Averaged parallel current density

Standard Dataset (interim 2/3)

- **Metric data**
  - **1D**: $V'(\rho)$, $\langle\nabla\rho\rangle(\rho)$, $\cdots$
  - **2D**: 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	$u_{s\phi}(\rho)$	$\mathrm{m/s}$	Toroidal rotation velocity

- **Kinetic plasma data**

FP	$f(p, \theta_p, \rho)$	momentum distribution at $theta = 0$

Standard Dataset (interim 3/3)

- **Dielectric tensor**

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

- **Full wave field data**

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

- **Ray trajectory wave field data**

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

Data Exchange Interface in BPSI

- **Data manipulation**
  - **Specify data**:
    — machine, shot, model, time
  - **Set data**:
    — 0D, 1D(ρ), 2D(ρ,χ), 2D(R,Z)
  - **Get data**:
    — 0D, 1D(ρ), 2D(ρ,χ), 2D(R,Z)
    — 0D(t), 1D(ρ,t), 2D(ρ,χ,t), 2D(R,Z,t)
- Define data
- Save data into a file
- Load data from a file
- Plot data

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

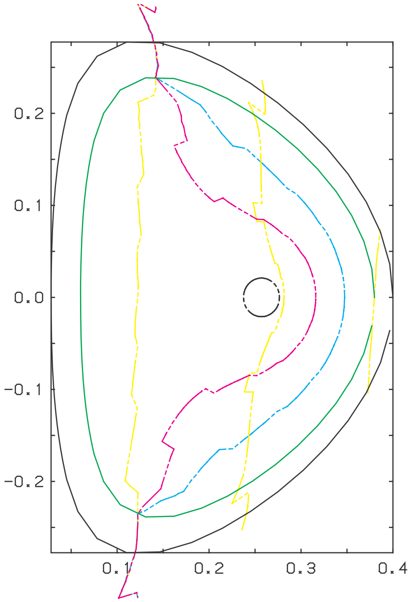
EQ/WM	Full Wave Analysis of ECH in a Small-Size ST
WM/FP/DP	Development of Self-Consistent Wave Analysis
EQ/TR	Transport Simulation for ITER
EQ/TR/MW/DP	Integrated Analysis of AE in ITER Plasma
WA	Full Wave Analysis of RWM
TX	Dynamical Transport Simulation including Rotation

Full Wave Analysis of ECH in a Small-Size ST

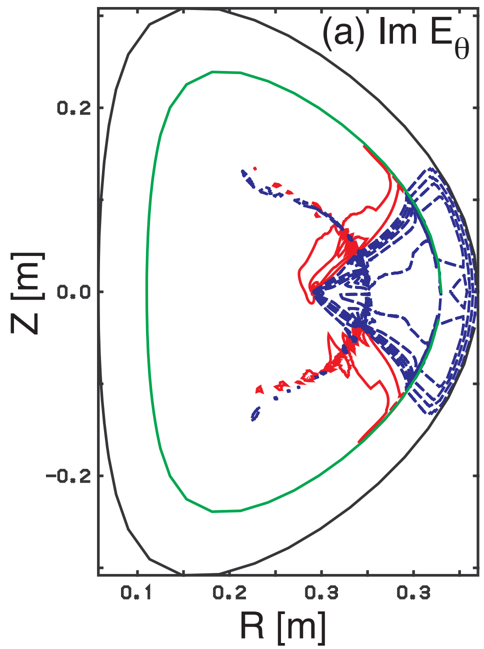
- **Small-size spherical tokamak: LATE** (Kyoto University)
  - **T. Maekawa et al., IAEA-CN-116/EX/P4-27 (Vilamoura, Portuga, 2004)**
  - $R = 0.22\,\mathrm{m}$, $a = 0.16\,\mathrm{m}$, $B_0 = 0.0552\,\mathrm{T}$, $I_p = 6.25\,\mathrm{kA}$, $\kappa = 1.5$
  - $f = 2.8\,\mathrm{GHz}$, Toroidal mode number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

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

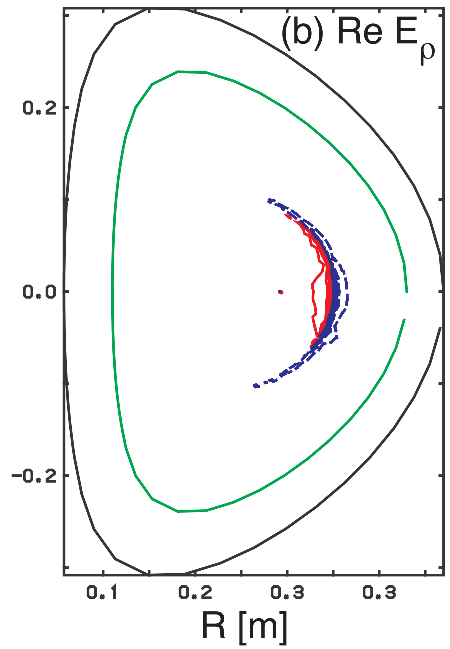
UHR,cutoff,



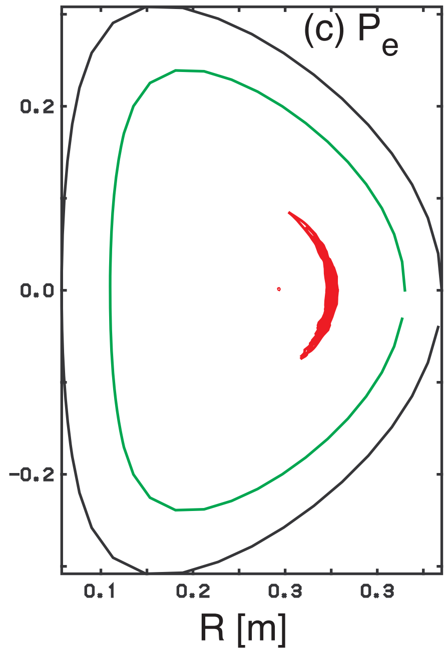
$\mathrm{Im}E_\theta$



$\mathrm{Re}E_\rho$

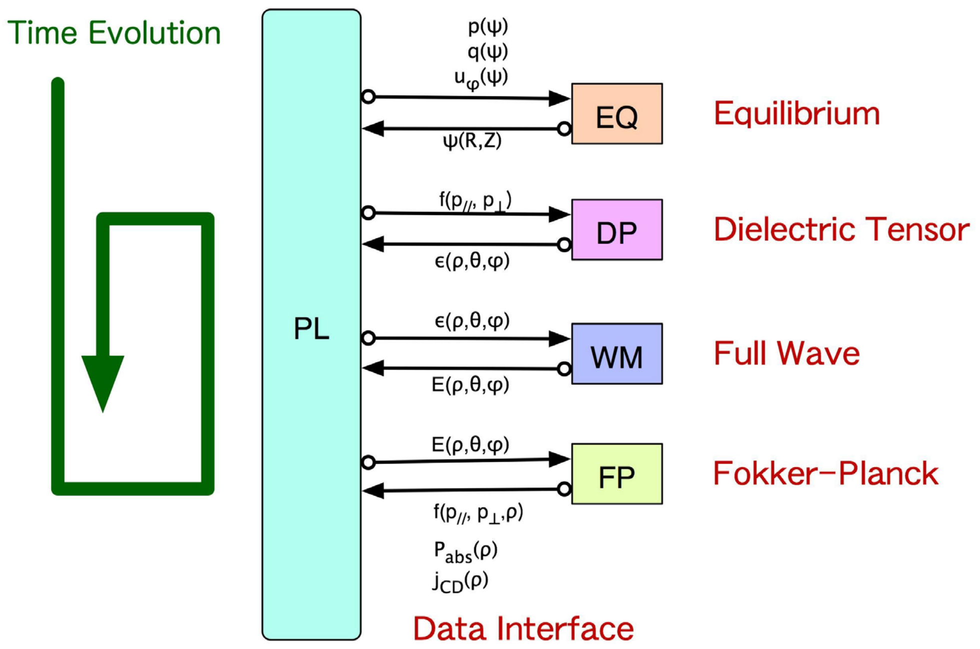


P_{abs}



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 $f(v)$**

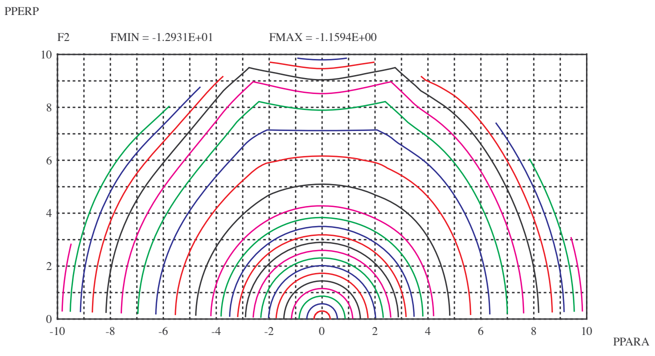


Development of Self-Consistent Wave Analysis

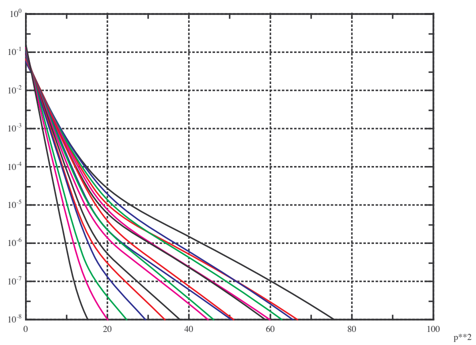
- **Code Development in TASK**
  - Ray tracing analysis with arbitrary $f(v)$: **Already done**
  - Full wave analysis with arbitrary $f(v)$: **Completed**
  - Fokker-Plank analysis of ray tracing results: **Already done**
  - Fokker-Plank analysis of full wave results: **Almost competed**
  - Self-consistent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

- **Tail formation by ICRF minority heating**

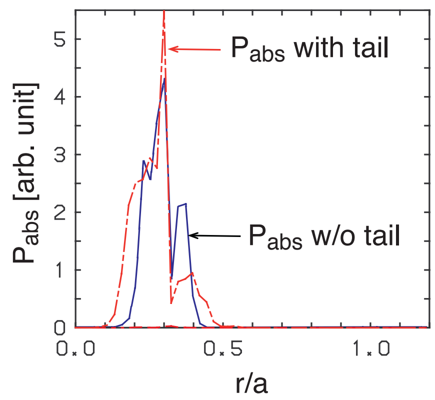
Momentum Distribution



Tail Formation



Power deposition



TASK/TR

- **1-D Diffusive Transport Simulation**
  - **Variables**:

Density	n_s for s = D, T, He, Impurity
Rotation	u_s for s = D, T, He, Impurity
Temperature	T_s for s = Electron, D, T, He, Impurity
Energy density	W_s for s = α, Beam ion
Neutral density	$n_{\mathrm{f}s}$ (fast) , $n_{\mathrm{s}s}$ (slow) for s = D, T
Impurity density	n_{Imp} for s = C^{6+}
Poloidal flux	$\partial\psi/\partial\rho$

  - **Diffusion equation**
  - **Transport coefficients**
    Neoclassical models **(Hinton & Hazeltine, Hirshman, Sauter, NCLASS)**
    Turbulent models **(CDBM, GLF23, IFS/PPPL, Weiland, Bohm/Gyro-Bohm)**
  - **Sources and Sinks**:
    Ionization, Radiation
    Collisional momentum and energy transfer
    Simple NB, RF heating and current drive
    Fusion reaction

CDBM Transport Model: CDBM05

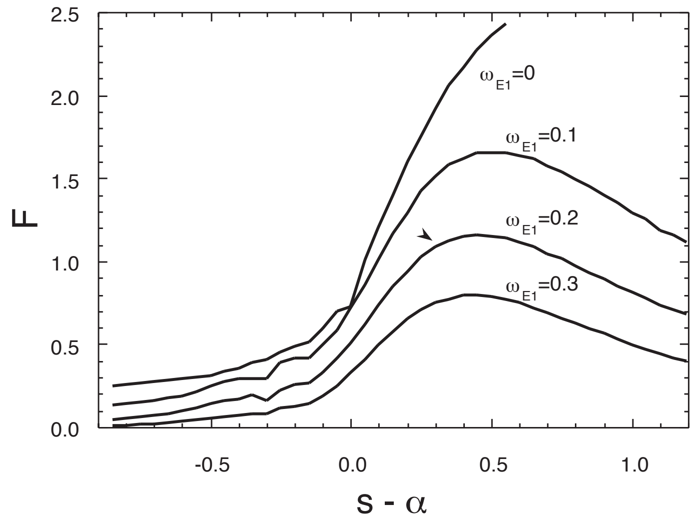
- **Thermal Diffusivity** (Marginal: $\gamma = 0$)

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

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

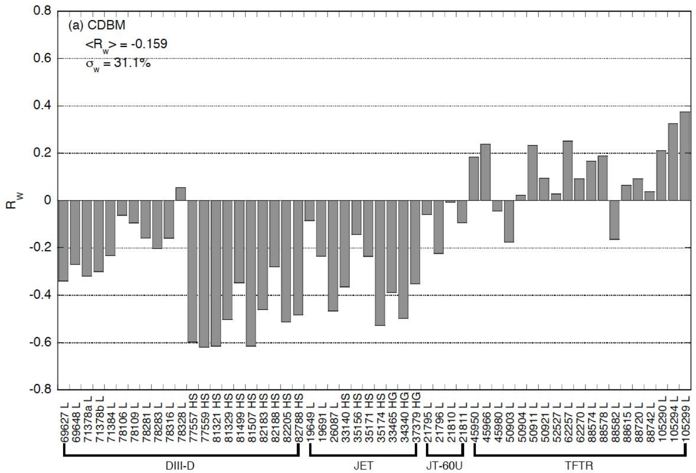


$$F(s, \alpha, \kappa, \omega_{\mathrm{E1}}) = \left(\frac{2\kappa^{1/2}}{1+\kappa^2}\right)^{3/2} \times \begin{cases} \dfrac{1}{1+G_1\omega_{\mathrm{E1}}^2} \dfrac{1}{\sqrt{2(1-2s')(1-2s'+3s'^2)}} & \text{for } s' = s - \alpha < 0 \\[2ex] \dfrac{1}{1+G_1\omega_{\mathrm{E1}}^2} \dfrac{1 + 9\sqrt{2}s'^{5/2}}{\sqrt{2}(1-2s'+3s'^2+2s'^3)}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

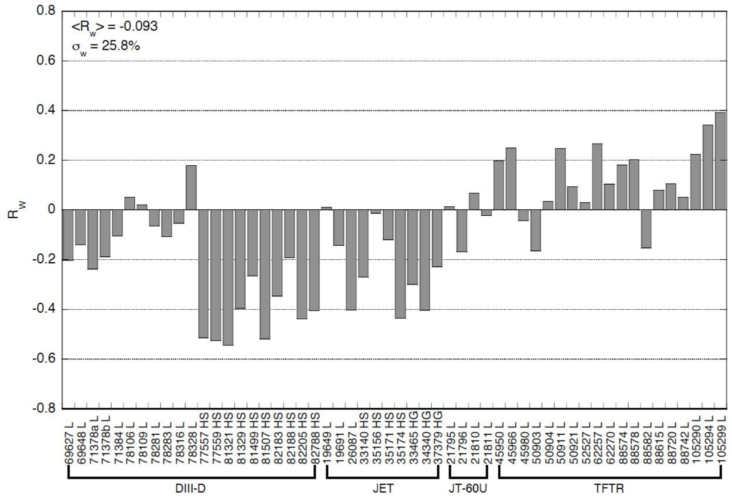
Comparison of Transport Models: ITPA Profile DB

Deviation of Stored Energy

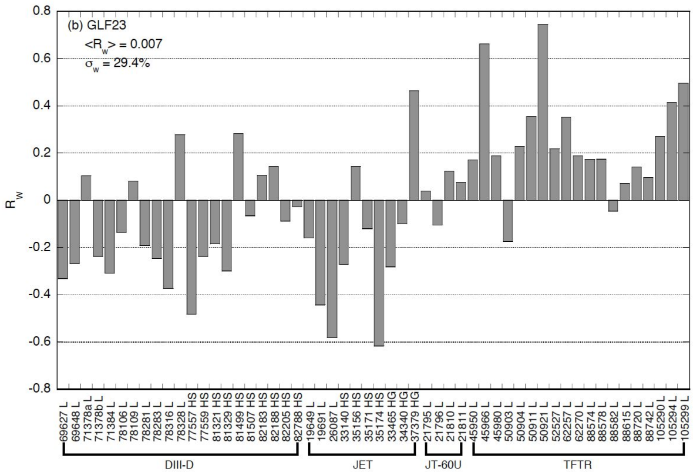
CDBM



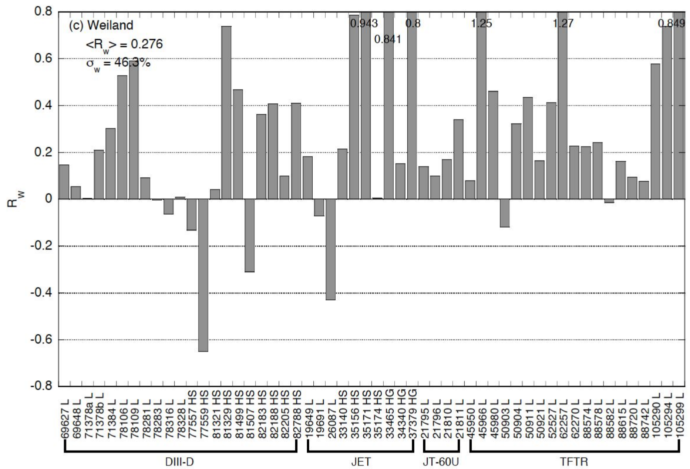
CDBM05



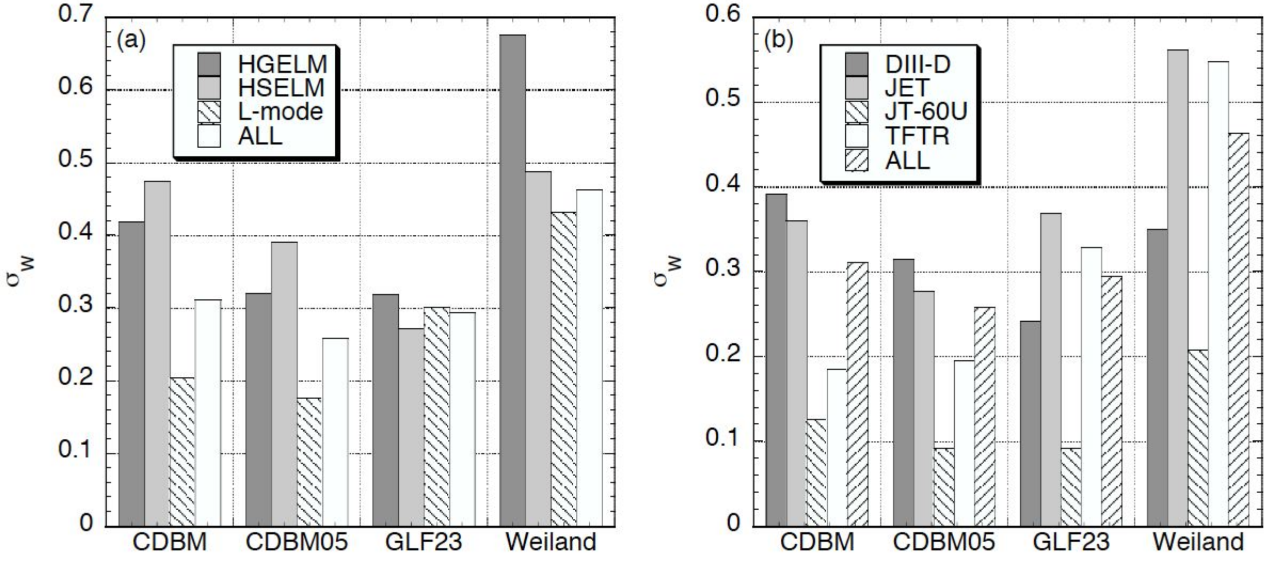
GLF23



Weiland



Dependence on Operation Mode and Devices



- Both CDBM05 and GLF23 reproduce the ITPA profile database pretty well.
- CDBM05 describes L-mode discharges better than GLF23.
- Both CDBM05 and GLF23 reproduces T_{i} much better than T_{e}, when the temperature of the other species is fixed to the experimental value.

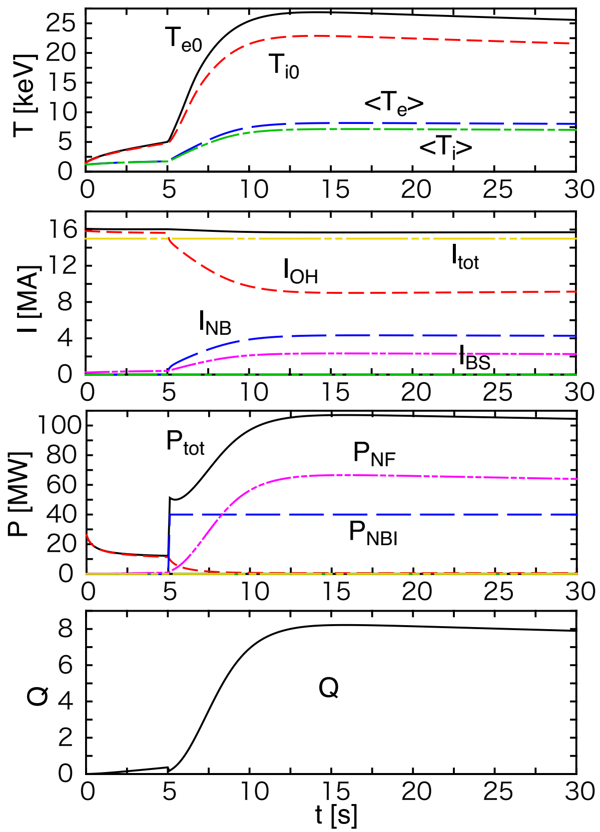
High Q Operational Scenario

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

CDBM

$\beta_N = 1.49$

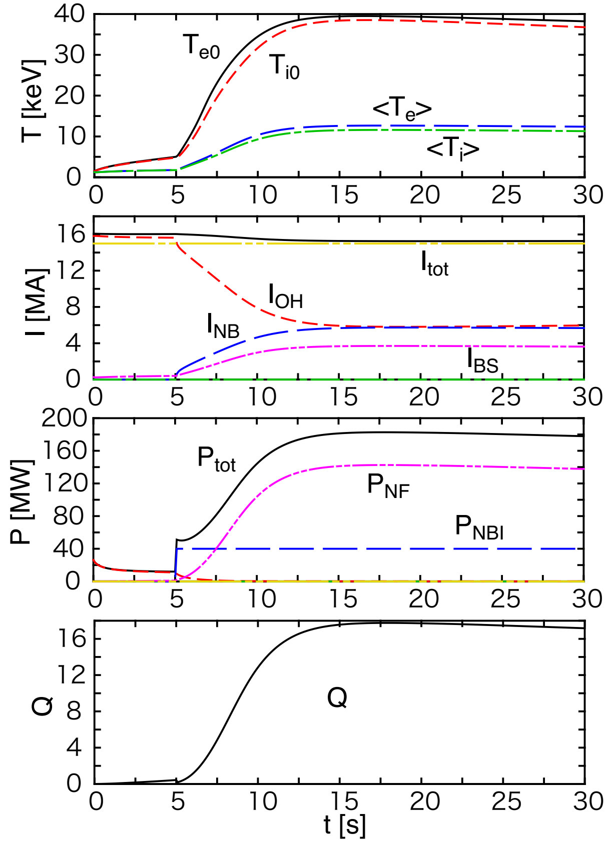
$\tau_E = 3.0$ s

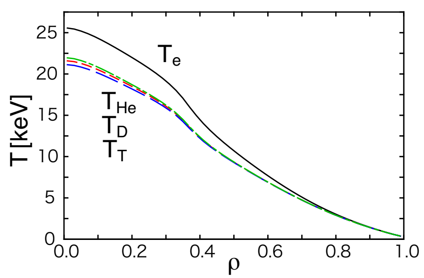


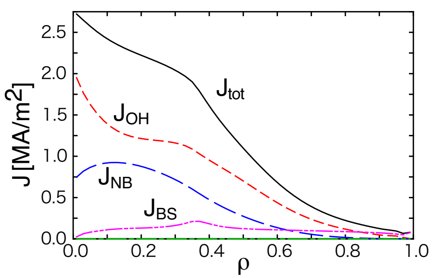
CDBM05

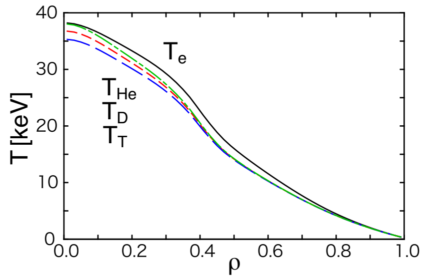
$\beta_N = 2.63$

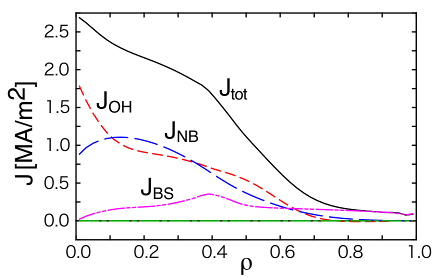
$\tau_E = 3.1$ s











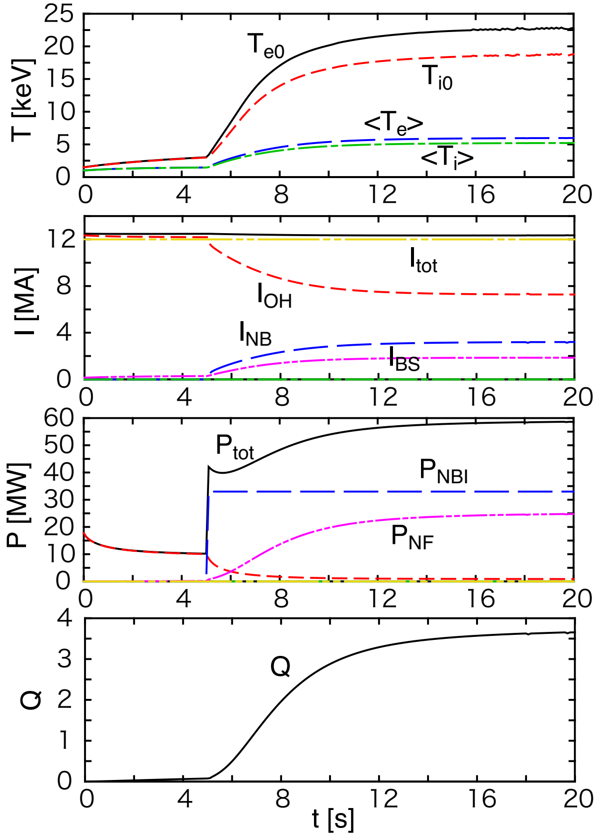
Hybrid Operational Scenario

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

CDBM

$\beta_N = 1.17$

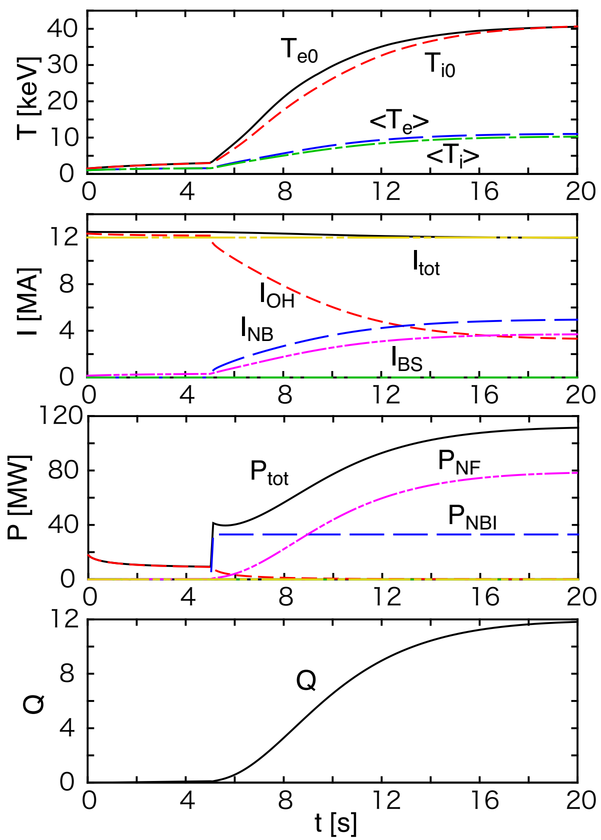
$\tau_E = 3.1$ s

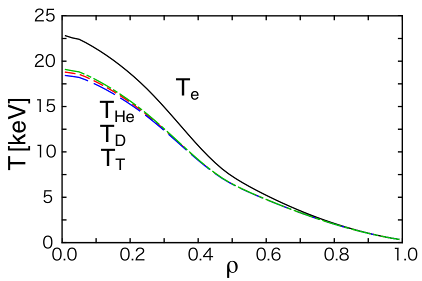


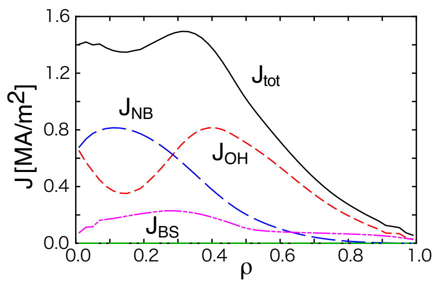
CDBM05

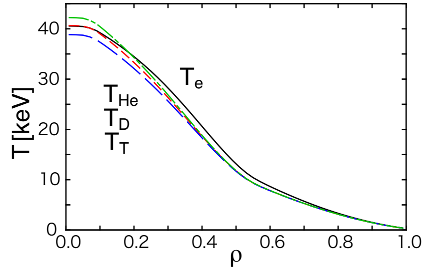
$\beta_N = 2.58$

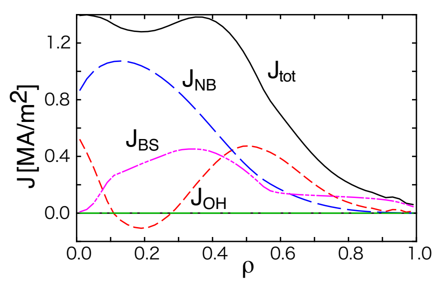
$\tau_E = 3.6$ s











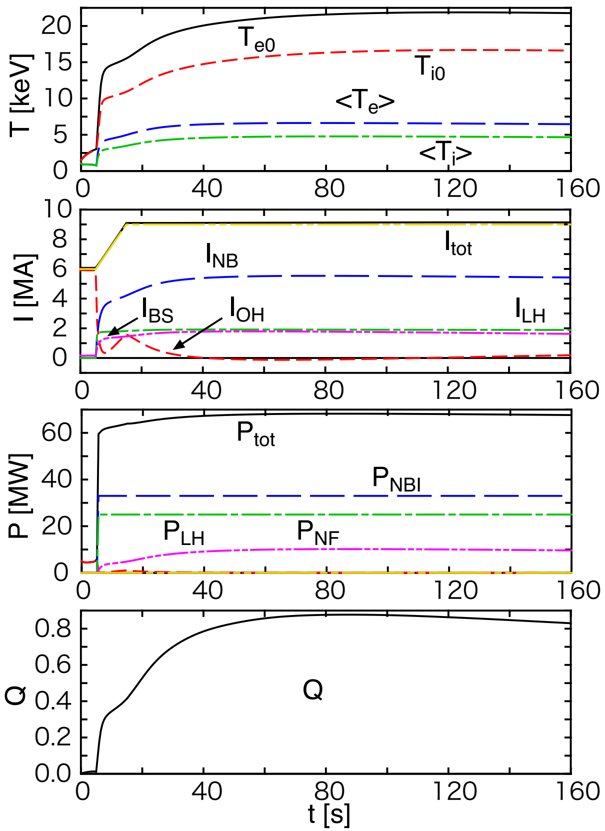
Quasi-Steady State Operational Scenario

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

CDBM

$\beta_N = 1.2$

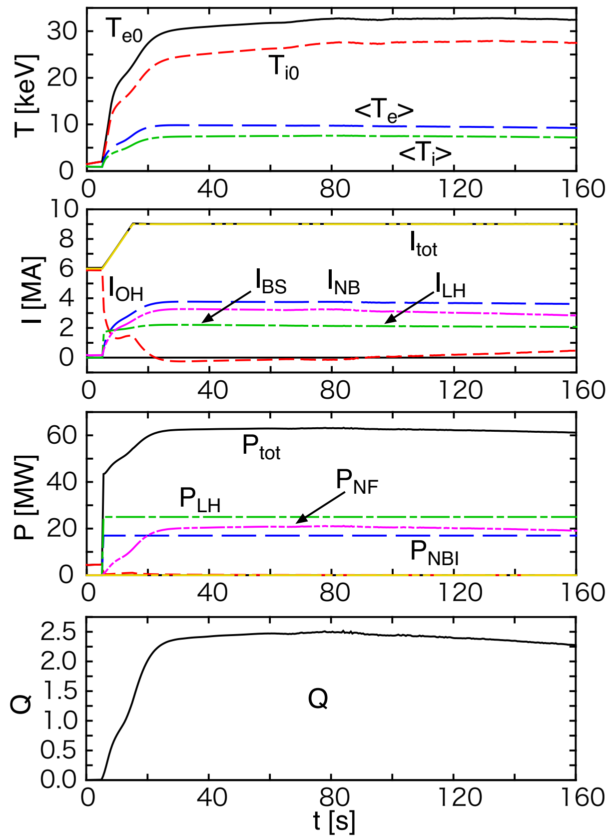
$\tau_E = 3.0$ s

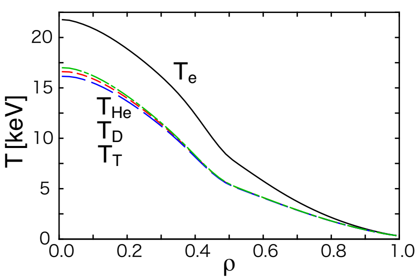


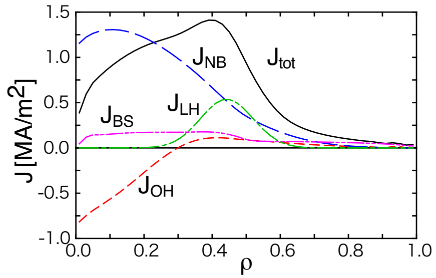
CDBM05

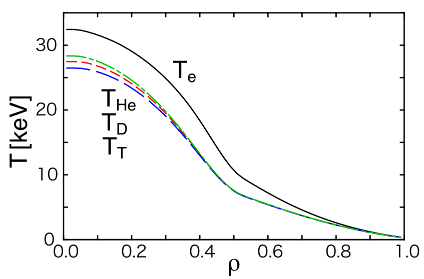
$\beta_N = 1.55$

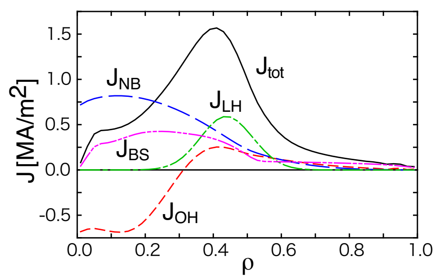
$\tau_E = 3.2$ s







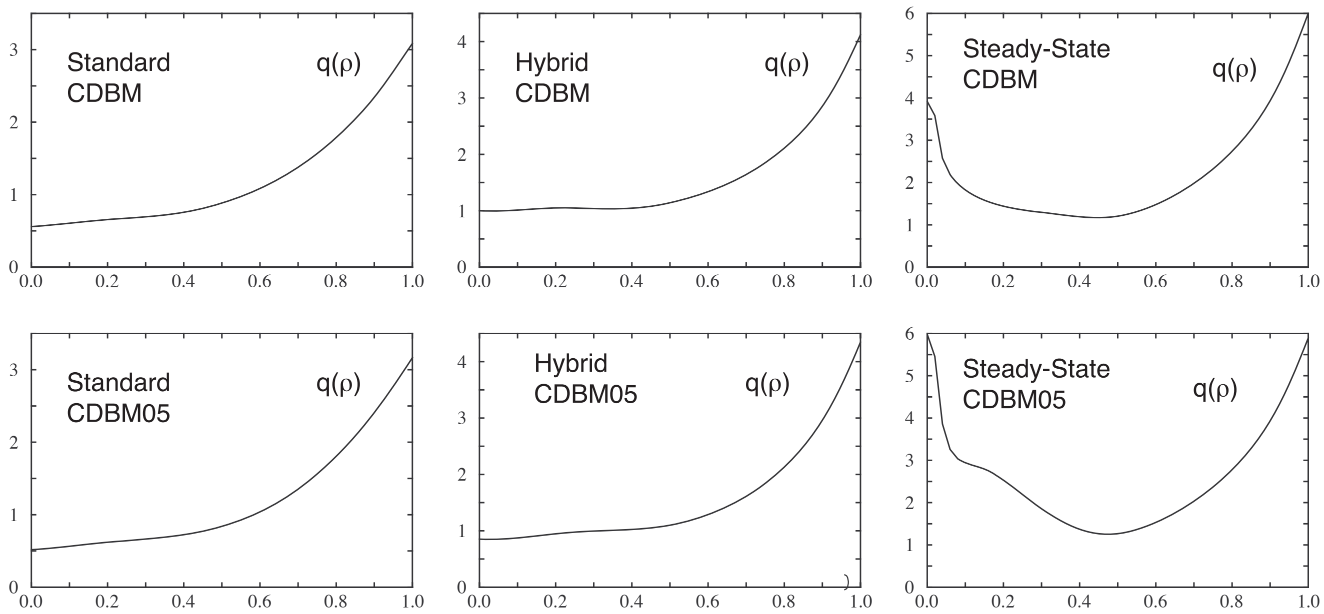




$P_{NB} = 35$ MW $P_{LH} = 30$ MW $P_{NB} = 17$ MW $P_{LH} = 25$ MW

q Profiles of Previous Shots

Standard **Hybrid** **Steady State**



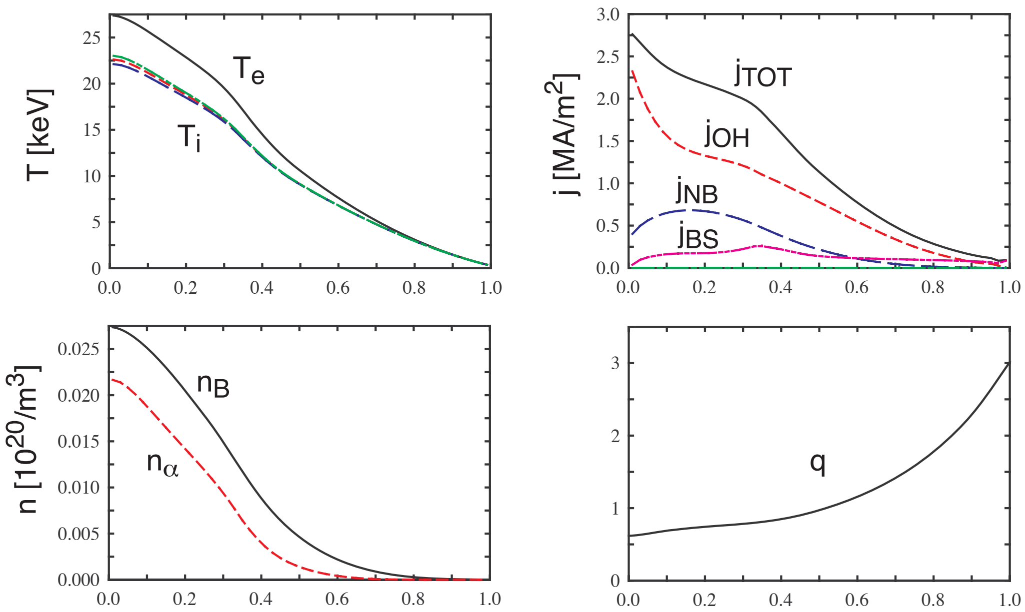
- Control of current profile in the hybrid operation requires more improvement to keep $q(0) > 1$.
- Performance of the quasi steady-state operation will be improved if the H-mode plasma edge (edge transport barrier) are included. .

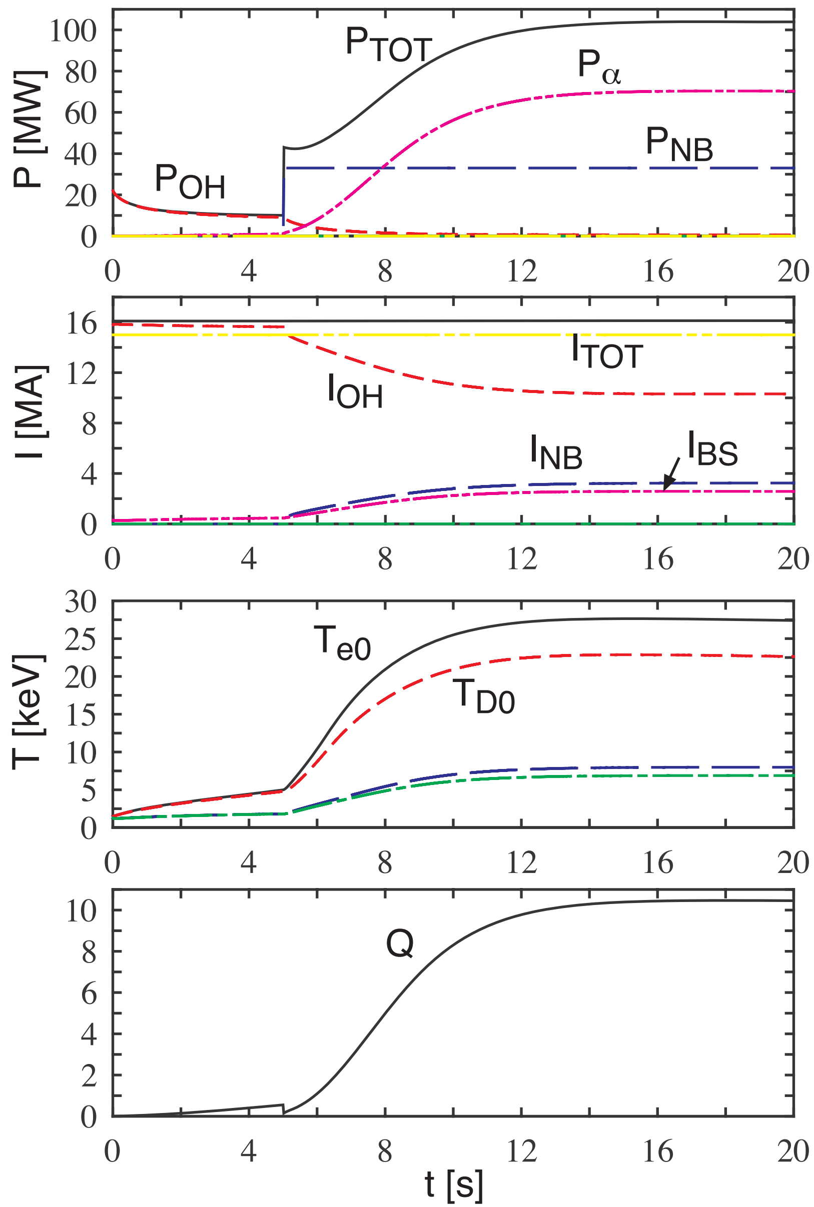
Integrated Analysis of AE in ITER Plasma

- **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: $I_{\mathrm{p}} = 15\,\mathrm{MA}$, $Q \sim 10$
  - Hybrid operation: $I_{\mathrm{p}} = 12\,\mathrm{MA}$, flat q profile above 1
  - Steady-state operation: $I_{\mathrm{p}} = 9\,\mathrm{MA}$, reversed shear

Standard H-mode Operation

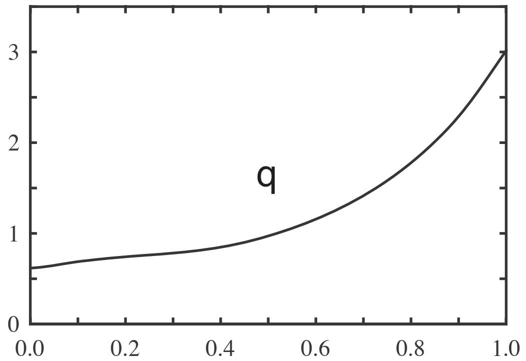
- $I_\mathrm{p} = 15\,\mathrm{MA}$
- $P_\mathrm{NB} = 33\,\mathrm{MW}$
- $\beta_\mathrm{N} = 1.3$



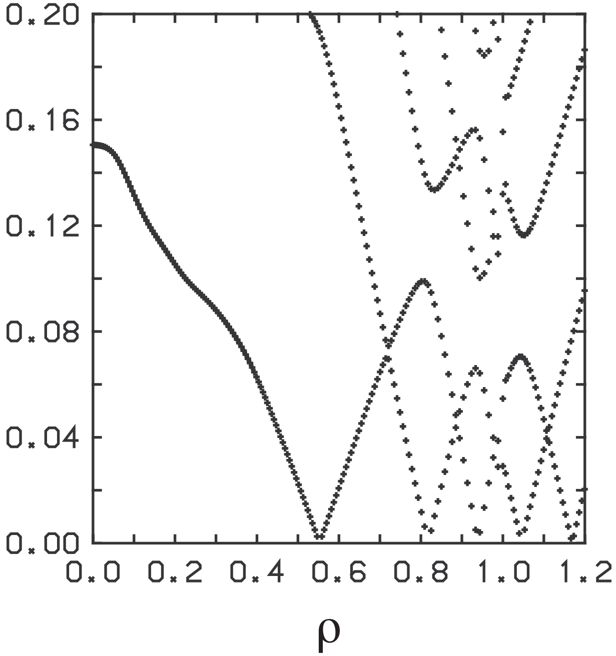


AE in Standard H-mode Operation

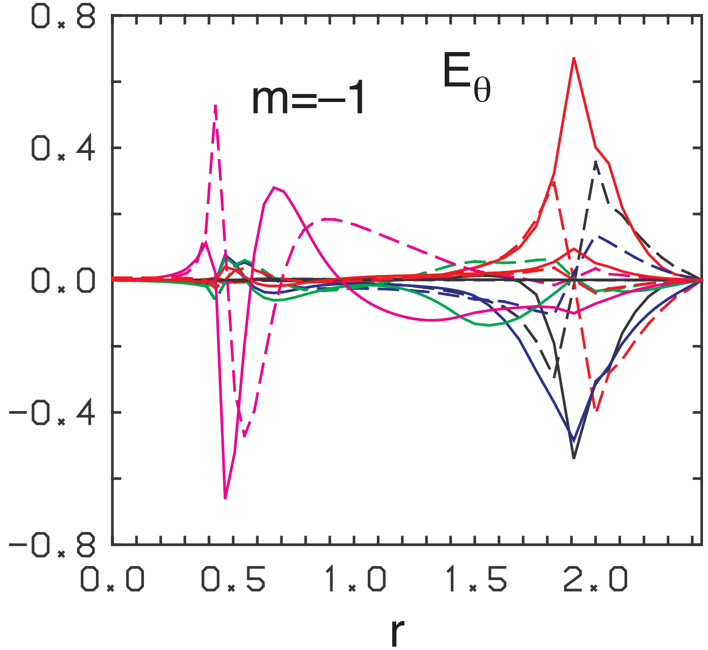
q profile



Alfvén Continuum



Mode structure ($n = 1$)



$f_r = 95.95\,\text{kHz}$
$f_i = -1.95\,\text{kHz}$

Stabilization due to $q = 1$

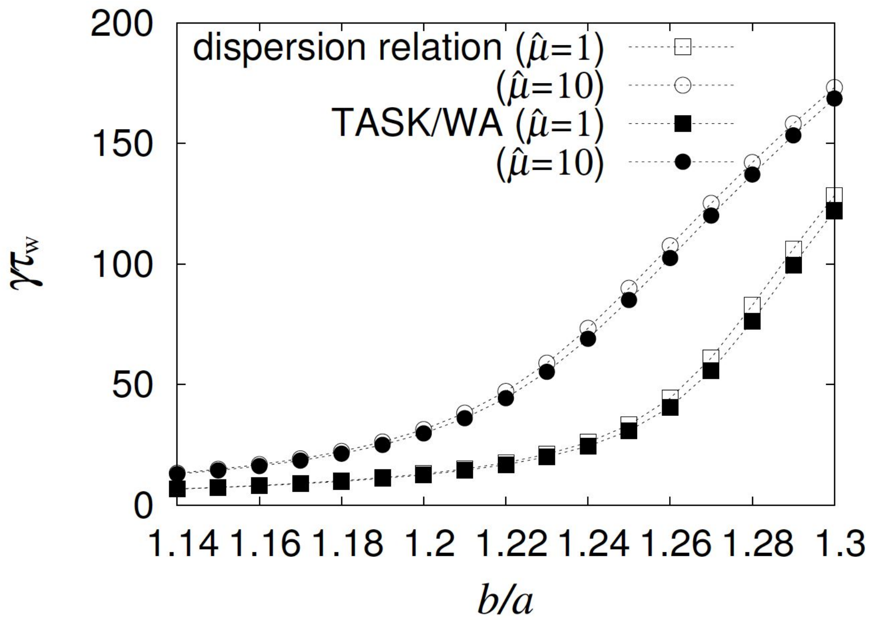
Full Wave Analysis of RWM (TASK/WA)

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

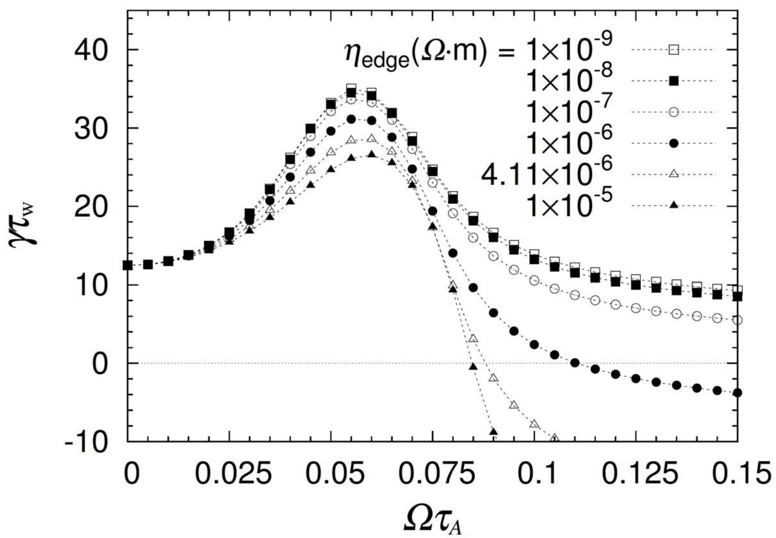
$$\nabla \times \nabla \times \boldsymbol{E} = \frac{\omega^2}{c^2} \overleftrightarrow{\epsilon} \cdot \boldsymbol{E} + \mathrm{i}\,\omega\mu_0 \boldsymbol{j}_{\mathrm{ext}}$$

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

b/a dependence



Rotation dependence



Summary

- The activity of **Burning Plasma Simulation Initiative** in Japan is gradually growing.
- We are developing **TASK** code as a reference core code for burning plasma simulation based on transport analysis.
- **Standard dataset** and **module interface** are still under discussion. They will be implemented by the end of this summer.
- **Future work for TASK**
  - Improvement of the modules: Full modular structure, Fortran95
  - Improvement of the models: Edge plasma, Sawtooth, ...
  - Systematic comparison with experimental data
  - Integrated simulation with other code: Stability, Peripheral, ...