Integrated Modeling of Tokamak Plasmas by TASK Code

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

Contents

• BPSI: Burning Plasma Simulation Initiative
• 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 → Korea**: one WS and a few PX per year expected
  - **Korea → 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/](http://bpsi.nucleng.kyoto-u.ac.jp/task/))
  - **Parallel Processing using MPI Library**
  - **Extension to Toroidal Helical Plasmas**
## Modules of TASK

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>EQ</td>
<td>2D Equilibrium</td>
<td>Fixed/Free boundary, Toroidal rotation</td>
</tr>
<tr>
<td>TR</td>
<td>1D Transport</td>
<td>Diffusive transport, Transport models</td>
</tr>
<tr>
<td>WR</td>
<td>3D Geometr. Optics</td>
<td>EC, LH: Ray tracing, Beam tracing</td>
</tr>
<tr>
<td>WM</td>
<td>3D Full Wave</td>
<td>IC, AW: Antenna excitation, Eigen mode</td>
</tr>
<tr>
<td>FP</td>
<td>3D Fokker-Planck</td>
<td>Relativistic, Bounce-averaged</td>
</tr>
<tr>
<td>DP</td>
<td>Wave Dispersion</td>
<td>Local dielectric tensor, Arbitrary $f(v)$</td>
</tr>
<tr>
<td>PL</td>
<td>Data Interface</td>
<td>Data conversion, Profile database</td>
</tr>
<tr>
<td>LIB</td>
<td>Libraries</td>
<td></td>
</tr>
</tbody>
</table>

### Under Development

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TX</td>
<td>Transport analysis including plasma rotation and $E_r$</td>
</tr>
<tr>
<td>WA</td>
<td>Global linear stability analysis</td>
</tr>
<tr>
<td>WI</td>
<td>Integro-differential wave analysis (FLR, $k \cdot \nabla B \neq 0$)</td>
</tr>
</tbody>
</table>

All developed in Kyoto U
Modular Structure of TASK

Experimental Database

- ITPA Profile DB
- JT-80 Exp. Data
- Simulation DB

Data Interface

- PL

Equilibrium
- EQ

Transport
- TR

Fokker-Planck
- FP

Ray Tracing
- WR

Full Wave
- WM

Wave Dispersion
- DP

Variables:
- $p(\psi), q(\psi), u_\psi(\psi)$
- $p, q, T, j_{CD}$
- $E(\rho, \theta, \phi)$
- $n, T, B, f(p_{\parallel}, p_{\perp})$
- $P_{abs}(R, Z, \phi)$

Functions:
- $\epsilon(\rho, \theta, \phi)$
- $\epsilon(R, Z, \phi)$
- $\epsilon$
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 \( \kappa \) Elongation at boundary
- RDLT \( \delta \) Triangularity at boundary
- RIP \( I_p \) A Typical plasma current

**Equilibrium data:** (Level 1)
- PSI2D \( \psi_p(R,Z) \) Tm\(^2\) 2D poloidal magnetic flux
- PSIT \( \psi_t(\rho) \) Tm\(^2\) Poloidal magnetic flux
- PSIP \( \psi_p(\rho) \) 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 \( \tilde{\epsilon}(\rho, \chi, \zeta) \) Local dielectric tensor

**Full wave field data**
- CE \( E(\rho, \chi, \zeta) \) V/m Complex wave electric field
- CB \( B(\rho, \chi, \zeta) \) Wb/m\(^2\) Complex wave magnetic field

**Ray/Beam tracing 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 \( \phi \) of ray at length \( \ell \)
- CERAY \( E(\ell) \) V/m Wave electric field at length \( \ell \)
- PWRAY \( P(\ell) \) W Wave power at length \( \ell \)
- DRAY \( d(\ell) \) m Beam radius at length \( \ell \)
- VRAY \( v(\ell) \) 1/m Beam curvature at length \( \ell \)
Execution Control Interface in BPSI

- **Example for TASK/TR**

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

- **Module registration**

  TR_STRUCT%INIT=TR_INIT
  TR_STRUCT%PARAM=TR_PARM
  TR_STRUCT%EXEC=TR_EXEC
  ...
  BPSX_REGISTER('TR',TR_STRUCT)
<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>EQ/WM</td>
<td>Full Wave Analysis of ECH in a Small-Size ST</td>
</tr>
<tr>
<td>WM/FP/DP</td>
<td>Development of Self-Consistent Wave Analysis</td>
</tr>
<tr>
<td>EQ/TR</td>
<td>Transport Simulation for ITER</td>
</tr>
<tr>
<td>EQ/TR/MW/DP</td>
<td>Integrated Analysis of AE in ITER Plasma</td>
</tr>
<tr>
<td>WA</td>
<td>Full Wave Analysis of RWM</td>
</tr>
</tbody>
</table>
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, Portugal, 2004)
  - $R = 0.22$ m, $a = 0.16$ m, $B_0 = 0.0552$ T, $I_p = 6.25$ kA, $\kappa = 1.5$
  - $f = 2.8$ GHz, Toroidal mode number $n = 12$, Extraordinary mode

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

![Graphs](image-url)
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

![Graphs showing momentum distribution, tail formation, and power deposition.](image-url)
CDBM Transport Model: CDBM05

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

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

- Magnetic shear

$$s \equiv \frac{r}{q} \frac{d}{dr}$$

- Pressure gradient

$$\alpha \equiv -q^2 R \frac{d\beta}{dr}$$

- Elongation

$$\kappa \equiv \frac{b}{a}$$

- $E \times B$ rotation shear

$$\omega_{E1} \equiv \frac{r^2}{s v_A} \frac{d}{dr} \frac{E}{r B}$$

- Weak and negative magnetic shear,

- Shafranov shift, elongation,

and $E \times B$ rotation shear

reduce thermal diffusivity.

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

\[
1 \quad \frac{1}{1 + G_1 \omega_{E1}^2 \sqrt{2}(1 - 2s')(1 - 2s' + 3s'^2)} \\
\text{for} \quad s' = s - \alpha < 0
\]

\[
1 \quad \frac{1}{1 + 9 \sqrt{2}s'^5/2} \\
\text{for} \quad s' = s - \alpha > 0
\]
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
High $Q$ Operational Scenario

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

\[
CDBM
\quad \beta_N = 1.49
\quad \tau_E = 3.0 \text{ s}
\]

\[
CDBM05
\quad \beta_N = 2.63
\quad \tau_E = 3.1 \text{ s}
\]
Hybrid Operational Scenario

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

\[ \beta_N = 1.17 \quad \tau_E = 3.1 \text{ s} \]

\[ \beta_N = 2.58 \quad \tau_E = 3.6 \text{ s} \]
**Quasi-Steady State Operational Scenario**

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

![Graphs showing temperature profiles and power dissipation](image)

**CDBM**
- $\beta_N = 1.2$
- $\tau_E = 3.0$ s

**CDBM05**
- $\beta_N = 1.55$
- $\tau_E = 3.2$ s

**Power Dissipation**

- $P_{NB} = 35$ MW
- $P_{LH} = 30$ MW

- $P_{NB} = 17$ MW
- $P_{LH} = 25$ MW
• 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: \( I_p = 15 \text{ MA}, Q \sim 10 \)
  - Hybrid operation: \( I_p = 12 \text{ MA}, \text{ flat } q \text{ profile above 1} \)
  - Steady-state operation: \( I_p = 9 \text{ MA}, \text{ reversed shear} \)
Standard H-mode Operation

- $I_p = 15$ MA
- $P_{NB} = 33$ MW
- $\beta_N = 1.3$
AE in Standard H-mode Operation

$q$ profile

Alfvén Continuum

Mode structure ($n = 1$)

$E_{\theta}$

$m = -1$

$f_r = 95.95$ kHz

$f_i = -1.95$ kHz

Stabilization due to $q = 1$
Full Wave Analysis of RWM (TASK/WA)

- **Full wave analysis**: solving Maxwell’s equation
  \[
  \nabla \times \nabla \times E = \frac{\omega^2}{c^2} \epsilon \cdot E + i \omega \mu_0 j_{\text{ext}}
  \]

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

**b/a dependence**

![Graph showing b/a dependence](image)

**Rotation dependence**

![Graph showing Rotation dependence](image)
# Future Plan of TASK code

## Present Status

<table>
<thead>
<tr>
<th>Equilibrium</th>
<th>Fixed/Free Boundary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core Transport</td>
<td>1D Diffusive TR</td>
</tr>
<tr>
<td></td>
<td>1D Dynamic TR</td>
</tr>
<tr>
<td>SOL Transport</td>
<td>2D Fluid TR</td>
</tr>
<tr>
<td>Neutral Transport</td>
<td>1D Diffusive TR</td>
</tr>
<tr>
<td>Energetic Ions</td>
<td>Kinetic Evolution</td>
</tr>
<tr>
<td>Wave Beam</td>
<td>Ray/Beam Tracing</td>
</tr>
<tr>
<td>Full Wave</td>
<td>Kinetic $\epsilon$</td>
</tr>
<tr>
<td>Stabilities</td>
<td>Sawtooth Osc.</td>
</tr>
<tr>
<td>Turbulent Transport</td>
<td>CDBM Model</td>
</tr>
</tbody>
</table>

## In 2 years

<table>
<thead>
<tr>
<th>Equilibrium Evolution</th>
<th>Kinetic TR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core Transport</td>
<td>2D Fluid TR</td>
</tr>
<tr>
<td>SOL Transport</td>
<td>Plasma-Wall Interaction</td>
</tr>
<tr>
<td>Neutral Transport</td>
<td>Orbit Following</td>
</tr>
<tr>
<td>Energetic Ions</td>
<td>Orbit Following</td>
</tr>
<tr>
<td>Wave Beam</td>
<td>Beam Propagation</td>
</tr>
<tr>
<td>Full Wave</td>
<td>Gyro Integral $\epsilon$</td>
</tr>
<tr>
<td>Stabilities</td>
<td>Tearing Mode</td>
</tr>
<tr>
<td>Turbulent Transport</td>
<td>Resistive Wall Mode</td>
</tr>
</tbody>
</table>

## In 5 years

<table>
<thead>
<tr>
<th>Start Up Analysis</th>
<th>Systematic Stability Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nonlinear ZK + ZF</td>
<td>Diagnostic Module</td>
</tr>
<tr>
<td></td>
<td>Control Module</td>
</tr>
</tbody>
</table>
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, sxfs90, · · ·)

- **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