Integrated Modeling of Burning Plasmas

A. Fukuyama

Department of Nuclear Engineering, Kyoto University

Acknowledgments
M. Honda, H. Nuga, and BPSI working group
Outline

1. Introduction
2. Integrated Modeling Code
3. Transport Modeling
4. Source Modeling
5. ITER Modeling
6. Summary
Integrated Simulation of Toroidal Plasmas

• Why needed?
  – To predict the behavior of burning plasmas in tokamaks
  – To develop reliable and efficient schemes to control them

• What is needed?
  – Simulation describing:
    ◦ Whole plasma (core & edge & divertor & wall-plasma)
    ◦ Whole discharge (startup & sustainment & transients events & termination)
    ◦ Reasonable accuracy (validation by experiments)
    ◦ Reasonable computer resources (still limited)

• How can we do?
  – Gradual increase of understanding and accuracy
  – Organized development of simulation system
Simulation of Tokamak Plasmas

Broad range of time scale:
100GHz $\sim$ 1000s

Broad range of Spatial scale:
10 $\mu$m $\sim$ 10m

One simulation code never covers all range.

Integrated simulation combining modeling codes interacting each other
Integrated Modeling Activities

- **Japan: BPSI** (Burning Plasma Simulation Initiative)
  - Research collaboration among universities, NIFS and JAEA
    - Integrated code framework
    - New physics models
    - Advanced computing

- **EU: ITM-TF** (EFDA Task Force: Integrated Transport Modeling)
  - Code Platform Project: code interface, data structure
  - Data Coordination Project: verification and validation
  - Five Integrated Modeling Projects: EQ, MHD, TR, Turb., Source

- **US: FSP** (Fusion simulation project) — presently a part of SciDAC
  - Simulation of Wave Interactions with Magnetohydrodynamics (SWIM)
  - Center for Plasma Edge Simulation (CPES)
  - Framework Application for Core-Edge Transport Simulations (FACETS)
Desired Features of Integrated Modeling Code

- **Modular structure**: for flexible extension of analyses
  - **Core modules** (equilibrium, transport, source, stability)
  - **Various levels of models** (quick, standard, precise, rigorous)
  - **New physics models** (easier development)

- **Standard module interface**: for efficient development of modules

- **Interface with experimental data**: for validating physics models

- **Unified user interface**: for user-friendly environment

- **Scalability in parallel processing** of time consuming modules

- **High portability**

- **Open source** of core modules

- **Visualization** included
Integrated Modeling Code: TASK

- **Transport Analysing System for TokamaK**
  - Developed in Kyoto University

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>EQ</td>
<td>2D Equilibrium Fixed/Free boundary, Toroidal rotation</td>
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<tr>
<td>TR</td>
<td>1D Transport Diffusive transport, Transport models</td>
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<tr>
<td>TX</td>
<td>1D Transport Dynamic Transport, Rotation and $E_r$</td>
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<tr>
<td>FP</td>
<td>3D Fokker-Planck Relativistic, Bounce-averaged</td>
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<td>WR</td>
<td>3D Ray tracing EC, LH: Ray tracing, Beam tracing</td>
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<td>WM</td>
<td>3D Full wave IC: Antenna excite, Alfvén Eigenmode</td>
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<td>DP</td>
<td>Wave Dispersion Dielectric tensor, Arbitrary $f(v)$</td>
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<td>FIT3D</td>
<td>NBI Physics Birth, Orbit width, Deposition</td>
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<td>PL</td>
<td>Utilities Interface to BPSD and profile database</td>
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<tr>
<td>LIB</td>
<td>Libraries Common libraries, MTX, MPI</td>
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- **TASK3D**: Extension to 3D Helical Plasmas (NIFS and Kyoto U)
Present Structure of the TASK code

Data Interface

Profile Database

Temporary DB

ITPA Profile DB

JT-60 Exp. Data

Simulation DB

BPSD

EQ

Fixed-boundary equilibrium

TR

Diffusive transport

TX

Dynamic transport

FP

Kinetic transport

WR

Ray and beam tracing

WM

Full wave analysis

DP

Wave dispersion

EG

Gyrokinetic microinstability

FIT3D

NBI analysis (birth, orbit, damping)

BPSD

EI

Helical current evolution

ER

Helical radial electric field

DCOM/NNW

Neoclassical coefficient database

VMEC

3D MHD equilibrium

TASK

TASK3D
**Data Exchange Interface: BPSD**

- **Standard dataset**: Specify data to be stored and exchanged
  - **Data structure**: Derived type (Fortran95): structured type
    
    | Time          | plasmaf%time |
    |---------------|--------------|
    | Number of grid| plasmaf%nrmax|
    | Number of species| plasmaf%nsmax|
    | Square of grid radius| plasmaf%s(nr) |
    | Plasma density  | plasmaf%data(nr,ns)%pn |
    | Plasma temperature| plasmaf%data(nr,ns)%pt |

- **Specification of API**:
  - **Program interface**
    
    | Set data   | bpsd_set_data(plasmaf,ierr) |
    | Get data   | bpsd_get_data(plasmaf,ierr) |
    | Save data  | bpsd_save(ierr)              |
    | Load data  | bpsd_load(ierr)              |
# BPSD Standard Dataset (version 0.6)

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Equilibrium Analysis

- **Shape of an axisymmetric plasma**: poloidal magnetic flux $\psi(R, Z)$

- **Grad-Shafranov equation**
  \[ R \frac{\partial}{\partial R} \left( \frac{1}{R} \frac{\partial \psi}{\partial R} \right) + \frac{\partial^2 \psi}{\partial Z^2} = -\mu_0 R^2 \frac{dp(\psi)}{d\psi} - F(\psi) \frac{dF(\psi)}{d\psi} \]

  - **Pressure profile**: $p(\psi)$
  - **Poloidal current density profile**: $F(\psi)$
  - **Plasma boundary shape** (fixed boundary) or **Poloidal coil current** (free boundary)

  determines the poloidal plasma shape.

- **Coupling with transport analysis**
  - **Input**: $p(\psi), q(\psi) = F \frac{dV}{d\psi} \left\langle \frac{1}{R^2} \right\rangle$
  - **Output**: Metric quantities, Flux surface averaged quantities
Various Levels of Transport Modeling

**Fluid model**
- Diffusive transport equation: $n(\rho,t), T(\rho,t)$
- Dynamic transport equation: $n(\rho,t), u(\rho,t), T(\rho,t), q(\rho,t)$

**Kinetic model**
- Bounce-averaged gyrokinetic equation: $f(p, \theta_p', \rho, t)$
- Axisymmetric gyrokinetic equation: $f(p, \theta_p', \rho, \chi, t)$
- Gyrokinetic equation: $f(p, \theta_p', \rho, \chi, \zeta, t)$
- Full kinetic equation: $f(p, \theta_p', \phi_g, \rho, \chi, \zeta, t)$
Transport Modeling in the TASK code

- **Diffusive transport equation**: TASK/TR
  - Diffusion equation for plasma density
  - Flux-Gradient relation
  - Conventional transport analysis

- **Dynamical transport equation**: TASK/TX:
  - Continuity equation and equation of motion for plasma density
  - Flux-averaged fluid equation
  - Plasma rotation and transient phenomena

- **Kinetic transport equation**: TASK/FP:
  - Gyrokinetic equation for momentum distribution function
  - Bounce-averaged Fokker-Plank equation
  - Modification of momentum distribution
Diffusive Transport Equation: TASK/TR

- **Transport Equation Based on Gradient-Flux Relation:**

  \[
  \Gamma = \hat{\mathbf{M}} \cdot \partial \mathbf{F} / \partial \rho
  \]

  where \( V \): Volume, \( \rho \): Normalized radius, \( V' = dV/d\rho \)

  - **Particle transport**

    \[
    \frac{1}{V'} \frac{\partial}{\partial t} (n_s V') = -\frac{\partial}{\partial \rho} \left( V' \langle |\nabla \rho| \rangle n_s V_s - V' \langle |\nabla \rho|^2 \rangle D_s \frac{\partial n_s}{\partial \rho} \right) + S_s
    \]

  - **Toroidal momentum transport**

    \[
    \frac{1}{V'} \frac{\partial}{\partial t} (n_s u_{\phi_s} V') = -\frac{\partial}{\partial \rho} \left( V' \langle |\nabla \rho| \rangle n_s u_{\phi_s} V_{M_s} - V' \langle |\nabla \rho|^2 \rangle n_s \mu_s \frac{\partial u_{\phi_s}}{\partial \rho} \right) + M_s
    \]

  - **Heat transport**

    \[
    \frac{1}{V'^{5/3}} \frac{\partial}{\partial t} \left( \frac{3}{2} n_s T_s V'^{5/3} \right) = -\frac{1}{V'} \frac{\partial}{\partial \rho} \left( V' \langle |\nabla \rho| \rangle \frac{3}{2} n_s T_s V_{E_s} - V' \langle |\nabla \rho|^2 \rangle n_s \chi_s \frac{\partial T_s}{\partial \rho} \right) + P_s
    \]

  - **Current diffusion**

    \[
    \frac{\partial B_\theta}{\partial t} = \frac{\partial}{\partial \rho} \left[ \frac{\eta}{FR_0 \langle R^{-2} \rangle} \frac{R_0 F^2}{\mu_0} \frac{\partial}{\partial \rho} \left( \frac{V' B_\theta}{F} \langle \frac{|\nabla \rho|^2}{R^2} \rangle \right) - \frac{\eta}{FR_0 \langle R^{-2} \rangle} \langle \mathbf{J} \cdot \mathbf{B} \rangle_{\text{ext}} \right]
    \]
Transport Processes

- **Neoclassical transport**
  - Collisional transport in an inhomogeneous magnetic field
  - **Radial diffusion**: usually small compared with turbulent diffusion
  - **Enhanced resistivity**: due to trapped particles
  - **Bootstrap current**: toroidal current driven by radial pressure gradient
  - **Ware pinch**: Radial particle pinch driven by toroidal electric field

- **Turbulent transport**
  - Various transport models: GLF23, CDBM, Weiland, · · ·

- **Atomic transport**: charge exchange, ionization, recombination

- **Radiation transport**
  - Line radiation, Bremsstrahlung, Synchrotron radiation

- **Parallel transport**: along open magnetic field lines in SOL plasmas
Turbulent Transport Models

- **CDBM model**: current diffusive ballooning mode turbulence model
  - developed by K. Itoh et al.
  - Marginal stability condition of the current diffusive ballooning mode including turbulent transport coefficients as parameters

- **GLF23 model**: Gyro-Landau-Fluid turbulence model
  - developed by Waltz and Kinsey (GA)
  - Linear growth rate from gyro-Landau-fluid model (ITG, TEM, ETG)
  - Evaluate transport coefficients based on mixing length estimate
  - Calibrate coefficients by the linear stability code GKS
  - Calibrate coefficients by the nonlinear turbulence code GYRO

- **Weiland model**:
  - developed by J. Weiland
  - Based on ITG turbulence model
GLF23 Transport Model

Linear growth rate from gyro-Landau-fluid model

Calibrate coefficients by the nonlinear turbulence code GYRO

Good agreement with experimental data
• **Thermal Diffusivity** (Marginal: $\gamma = 0$)

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

\[
\begin{align*}
\text{Magnetic shear} & \quad s \equiv \frac{r}{q} \frac{dq}{dr} \\
\text{Pressure gradient} & \quad \alpha \equiv -q^2 R \frac{d\beta}{dr} \\
\text{Elongation} & \quad \kappa \equiv b/a \\
\text{\textit{E} x \textit{B} rotation shear} & \quad \omega_{E1} \equiv \frac{r^2}{sv_A} \frac{d}{dr} \frac{E}{rB}
\end{align*}
\]

• Weak and negative magnetic shear, Shafranov shift, elongation, and \textit{E} x \textit{B} rotation shear reduce thermal diffusivity.

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

\[
\begin{align*}
1 & \quad 1 \\
1 + G_1 \omega_{E1}^2 & \quad \sqrt{2(1 - 2s')(1 - 2s' + 3s'^2)} \\
\text{for} & \quad s' = s - \alpha < 0 \\
1 + 9 \sqrt{2s'^{5/2}} & \quad 1 \\
1 + G_1 \omega_{E1}^2 & \quad \sqrt{2(1 - 2s' + 3s'^2 + 2s'^3)} \\
\text{for} & \quad s' = s - \alpha > 0
\end{align*}
\]
TFTR #88615 (L-mode, NBI heating)
DIII-D #78316 (L-mode, ECH and ICH heatings)
Comparison of Transport Models: ITPA Profile DB

Deviation of Stored Energy

CDBM

CDBM05

GLF23

Weiland
Modeling of Transport Barrier Formation

- Reduction of $D$
- Reduction of $X_e$
- Reduction of $X_i$
- Reduction of $\mu$

- Steepening of $n$ profile
- Steepening of $T_e$ profile
- Steepening of $T_i$ profile
- Steepening of $V_\phi$ profile

- Steepening of $p_e$ profile
- Steepening of $p_i$ profile
- Change of $V_\phi$ profile

- Increase of $J_{BS}$
- Increase of $\alpha$
- Increase of $E_r$

- Decrease of magnetic shear
- Increase of Shafranov shift
- Increase of ExB rotation shear
- Increase of $V_\phi$ rotation shear
High \( \beta_p \) mode

- \( R = 3 \, \text{m}, \, a = 1.2 \, \text{m}, \, \kappa = 1.5, \, B_0 = 3 \, \text{T}, \, I_p = 1 \, \text{MA} \)

- one second after heating power of \( P_H = 20 \, \text{MW} \) was switched on

Temperauter profile

Current profile

Safety factor

Shear and pressure

Thermal diffusivity

\( s - \alpha \) diagram
Steady State ITB Simulation

- CDBM transport model including velocity shearing rate
- Radial electric field calculated from the radial force balance

Heat transport simulation for the ITB shot #29728 on the JT-60U Tokamak

It is generally rather difficult to reproduce ITB formation.
Time Evolution of Internal Transport Barrier

- $P_H = 20 \text{ MW}$

- $P_H = 24.2 \text{ MW}$

Fukuyama et al. NF (1995)
1D Dynamic Transport Code: TASK/TX

- **Dynamic Transport Equations** (TASK/TX)

  M. Honda and A. Fukuyama, JCP 227 (2008) 2808

  - A set of flux-surface averaged equations
  - Two fluid equations for electrons and ions
    - Continuity equations
    - Equations of motion (radial, poloidal and toroidal)
    - Energy transport equations
  - Maxwell’s equations
  - Slowing-down equations for beam ion component
  - Diffusion equations for two-group neutrals

- **Self-consistent description of plasma rotation and electric field**
  - Equation of motion rather than transport matrix

- **Quasi-neutrality is not assumed.**
Model Equation of Dynamic Transport Simulation

- Flux-surface-averaged multi-fluid equations:

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

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

\[
+ F_{s\theta}^{NC} + F_{s\theta}^C + F_{s\theta}^W + F_{s\theta}^X + F_{s\theta}^L
\]

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

\[
+ F_{s\theta}^C + F_{s\theta}^W + F_{s\theta}^X + F_{s\theta}^L
\]

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

\[
+ F_{s\phi}^C + F_{s\phi}^W + F_{s\phi}^X + F_{s\phi}^L
\]

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

\[
+ P_s^C + P_s^L + P_s^H
\]
Typical Ohmic Plasma Profiles at $t = 50$ ms

JFT-2M like plasma composed of electron and hydrogen

$R = 1.3 \text{ m}$, $a = 0.35 \text{ m}$, $b = 0.4 \text{ m}$, $B_{\phi b} = 1.3 \text{ T}$, $I_p = 0.2 \text{ MA}$, $S_{\text{puff}} = 5.0 \times 10^{18} \text{ m}^{-2}\text{s}^{-1}$

$\gamma = 0.8$, $Z_{\text{eff}} = 2.0$, Fixed turbulent coefficient profile
Density Profile Modification Due to NBI Injection

Modification of $n$ and $E_r$ profile depends on the direction of NBI.

Co/Counter with $I_p$: Density flattening/peaking
Toroidal Rotation Due to Ion Orbit Loss

- Ion orbit loss near the edge region drives toroidal rotation

Ref. M. Honda et al., NF (2008) 085003
Source Modeling

- **Heat and momentum sources:**
  - **Alpha particle heating:**
    - sensitive to fuel density and momentum distribution
  - **Neutral beam injection:**
    - birth profile, finite size orbit, deposition to bulk plasma
  - **Waves:**
    - IC ($\sim 50$ MHz): fuel ion heating, current drive, rotation drive(?)
    - LH ($\sim 10$ GHz): current drive
    - EC ($\sim 170$ GHz): current drive, pre-ionization

- **Particle source**
  - **Gas puff, recycling:**
  - **Neutral beam injection:**
  - **Pellet injection:** penetration, evaporation, ionization, drift motion
Wave Modeling

- **Ray tracing**: EC, LH
  - Spatial evolution of ray position and wave number
  - Wave length $\lambda$ much less than scale length $L$: $\lambda \ll L$
  - Beam size $d$ is sufficiently large (**Fresnel condition**): $L \ll \frac{d^2}{\lambda}$

- **Beam tracing**: EC
  - New variables: beam radius, curvature of wave equi-phase surface

- **Full wave analysis**: IC, AW, MHD
  - Stationary Maxwell’s equation as a boundary problem
  - Wave length $\lambda$ comparable with scale length $L$
  - Evanescent region, strong absorption, coupling with antenna
  - Not easy to include kinetic effects in inhomogeneous plasmas
Momentum Distribution Function

- **Fokker-Planck equation**
  for velocity distribution function $f(p_\parallel, p_\perp, \psi, t)$
  
  $\frac{\partial f}{\partial t} = E(f) + C(f) + Q(f) + L(f)$
  
  - $E(f)$: 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 $p$, weakly relativistic collision term
- **Nonlinear collision**: momentum or energy conservation
- **Three-dimensional**: spatial diffusion (neoclassical, turbulent)
Analysis of ECCD by the TASK Code

Poloidal angle 70°
Toroidal angle 20°
Initial beam radius 0.05 m
Initial beam curvature 2 m

Ray/Beam Profile

$P_{abs}$ Profile

$j_{CD}$ Profile
Full wave analysis: TASK/WM

- **magnetic surface coordinate**: \((\psi, \theta, \varphi)\)

- Boundary-value problem of **Maxwell’s equation**

  \[
  \nabla \times \nabla \times E = \frac{\omega^2}{c^2} \epsilon \cdot E + i \omega \mu_0 j_{\text{ext}}
  \]

- Kinetic **dielectric tensor**: \(\epsilon\)
  - **Wave-particle resonance**: \(Z[(\omega - n\omega_c)/k || v_{\text{th}}]\)
  - **Fast ion: Drift-kinetic**

    \[
    \left[ \frac{\partial}{\partial t} + v_{||} \nabla_{||} + (v_d + v_E) \cdot \nabla + \frac{e\alpha}{m\alpha} (v_{||} E_{||} + v_d \cdot E) \frac{\partial}{\partial \varepsilon} \right] f_\alpha = 0
    \]

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

- **Modification of velocity distribution from Maxwellian**
  - Energetic ions generated by ICRF waves
  - Alpha particles generated by fusion reaction
  - Fast ions generated by NB injection

- **Self-consistent wave analysis including modification of $f(v)$**

![Diagram showing time evolution and data interface with symbols for equilibrium (EQ), dielectric tensor (DP), full wave (WM), Fokker–Planck (FP), and data interface.](image)
Preliminary Results

- Tail formation by ICRF minority heating

Quasi-linear Diffusion  Momentum Distribution

Wave pattern

Tail Formation

Power deposition
ITER Modeling Needs

based on Dr. Campbell’ talk at Cadarache, Sept 2007

• **Plasma scenario development:**
  – Preparation for operation

• **Detailed design of auxiliary systems:**
  – H&CD, Diagnostics, Fueling, · · ·

• **Design of plasma control system:**
  – Development and optimization of integrated control strategies

• **Preparation of ITER operational programme:**
  – End-to-end scenario development
  – Detailed pulse definition

• **Experimental data evaluation:**
  – Pulse characterization and physics analysis
  – Refinement of operation scenario and performance predictions
ITER Plasma Transport Simulation with CDBM05

**Inductive operation**
- $I_p = 15$ MA
- $P_{NB} = 40$ MW on axis
- $\beta_N = 2.65$

**Hybrid operation**
- $I_p = 12$ MA
- $P_{NB} = 33$ MW on axis
- $\beta_N = 2.68$
Alfvén Eigenmode Analysis by TASK/WM

- **Alfvén eigenmode driven by alpha particles**
  - Calculated by the full wave module TASK/WM
  - Toroidal mode number: \( n = 1 \)
  - TAE is stable: Eigen mode frequency = (95.95 kHz, −1.95 kHz)
Modeling of Steady-State Operation


Simulation result by GLF23

Dependence on pedestal temperature
Integrated ELM Modeling by JAEA

1.5D core transport code (TOPICS)
1D transport & current diffusion equations
2D Grad-Shafranov equation

[Note: N. Hayashi, IAEA FEC 2006]

2D MHD equilibrium

ELM model: Enhance transport

Heat & particle flows across separatrix

Boundary conditions at separatrix

Eigenvalue & Eigenfunction

2D MHD stability code (MARG2D)
Eigenvalue problem of 2D Newcomb equation
Applicable to wide range of mode numbers from low to high

SOL-divertor model (Five-point model)
Flux-tube geometry
Integral fluid equations
Exponential radial profiles with characteristic scale length

Linear MHD stability code (MARG2D)
Eigenvalue problem of 2D Newcomb equation
Applicable to wide range of mode numbers from low to high
Energy loss by ELMs is crucial for reducing the divertor plate lifetime and limiting the plasma confinement. ELM energy loss was found to decrease with increasing the collisionality in multi-machine experiments. The collisionality dependence is investigated. ELM phenomena is simulated in JT-60 parameters.

Pedestal formation: Neoclassical transport in peripheral region and anomalous in inside region. Stabilities of n=1-30 modes are examined in each time step.
Integrated SOL-Divertor Code by JAEA

Remaining Issues

- **Pedestal temperature**: modeling of L/H transition
- **Transport barrier formation**: turbulence transport model
- **ELM physics**: nonlinear behavior of ELM on transport
- **Nonlinear MHD events**: modeling of plasma profile change
- **Energetic-ion driven phenomena**: coupling of Alfvén mode and drift waves
- **Kinetic analysis of transport and MHD phenomena**: non-Maxwellian distribution
- **Wave physics**: full wave analysis of Bernstein waves
- **Divertor plasma**: plasma-wall interaction
- **Start up**: Rapid change of equilibrium and control

and so on...
Summary

• **Integrated modeling of burning plasmas** is indispensable for exploiting optimized operation scenario of ITER and reliable design of DEMO.

• Discussion on **international collaboration** for the development of **integrated ITER modeling** is on going.

• There are **many remaining issues** in **constructing comprehensive integrated code**; especially, L/H transition mechanism, turbulent transport model, ELM physics, nonlinear MHD events, energetic particle driven phenomena and plasma wall-interactions.

• Solving those remaining issues requires not only **large-scale computer simulations** but also **intensive modeling efforts** based on experimental observations.