Present Status and Future of Simulation Research on Burning Plasmas

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- Introduction
- BPSI/TASK
- Simulation of burning plasmas
- Summary
Burning Plasma Research

How to create burning plasmas?
- good confinement
- sufficient stability
- efficient heating

What is new in burning plasmas?
- highly autonomous
- energetic particles
- high heat flux

How to control burning plasmas?
- burning control
- stability control
- ELM control
What is new in burning plasmas?

Highly autonomous

Present Plasma

- Induction
- Current Drive
- Current Profile
- Bootstrap Current
- RF
- Heating
- Pressure Profile
- Alpha Heating
- NBI
- Fueling
- Fuel Ion Profile
- Turbulent Transport
- Pellet Injection
- Rotation Drive
- Rotation Profile
What is new in burning plasmas?

Highly autonomous

Burning Plasma
What is new in burning plasmas?

Highly autonomous

Steady-State Burning Plasma

- Induction
- RF
- NBI
- Pellet Injection
- Current Drive
- Heating
- Fueling
- Rotation Drive
- Current Profile
- Pressure Profile
- Fuel Ion Profile
- Rotation Profile
- Bootstrap Current
- Alpha Heating
- Turbulent Transport

Induction

Current Drive

Heating

Fueling

Rotation Drive

Current Profile

Pressure Profile

Fuel Ion Profile

Rotation Profile

Bootstrap Current

Alpha Heating

Turbulent Transport
What is new in burning plasmas?

Energetic Particles
- Particle phenomena
  - Plasma heating
  - Orbit loss
- Collective phenomena
  - Alfvén eigenmode
  - Channeling

High Heat Flux
- SOL and divertor plasma
- Plasma-wall interaction
Role of Simulation in Burning Plasmas

**First principle simulation**
- Turbulence  gyrokinetic simulation
- Global instability  extended MHD

**Component simulation**
- Transport phenomena (core, SOL, diverter)
- MHD phenomena (RWM, NTM, Sawtooth, ELM, ...)
- Wave-particle interaction (EC, LH, IC, AE)

**Integrated simulation**
- Integration of various physical phenomena
Integrated 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** (comparison with experiments)
    - **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

BPSI Working Group

Universities
- JAEA
- NIFS
- CRIEPI

since 2003
Targets of BPSI

- **Framework** for collaboration of various plasma simulation codes
  - **Common interface** for data transfer
  - **Reference core code**, TASK
  - **Helical configuration** included

- **New Physics** in interactions of phenomena with different time and space scales (e.g.)
  - **Transport during and after a transient MHD events**
  - **Transport in the presence of magnetic islands**
  - **Core-SOL interface**

- **Advanced technique** of computer science
  - **Parallel computing**: PC cluster, Massively Parallel, Vector-Parallel
  - **Distributed computing**: GRID computing, Globus, ITBL
  - **Visualization**: Parallel visualization, VisiGRID
TASK: as a core code of BPSI

Universities and Institute

JAERI
- MARG2D
- OFMC
- TOPICS

BPSI

NIFS
- TAE
- HINT

GNET
- ...

TASK
TASK code

- Transport Analysing System for Tokamak

- Features
  - A Core of Integrated Modelling Code in BPSI
    - Modular Structure
    - Reference Data Interface
  - Various Heating and Current Drive Scheme
    - EC, LH, IC, AW, (NB)
  - High Portability
    - Most of Library Routines Included (except LAPACK)
    - Own Graphic Libraries (gsaf, gsgl)
  - Development using CVS (Concurrent Version System)
    - Open Source (by the end of 2004)
  - Parallel Processing using MPI Library
  - Extension to Toroidal Helical Plasmas
## Modules of TASK code

<table>
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<th>EQ</th>
<th>2D Equilibrium</th>
<th>Fixed boundary, Toroidal rotation</th>
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<td>Diffusive Transport, Transport models</td>
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<td>3D Geometr. Optics</td>
<td>EC, LH: Ray tracing, Beam tracing</td>
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<td>WM</td>
<td>3D Full Wave</td>
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<td>FP</td>
<td>3D Fokker-Planck</td>
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<td>Wave Dispersion</td>
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<td>Data Interface</td>
<td>Data conversion, Profile database</td>
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<td>LIB</td>
<td>Libraries</td>
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### Associated Libraries

<table>
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<tr>
<th>GSAF</th>
<th>2D Graphic library for X Window and EPS</th>
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</thead>
<tbody>
<tr>
<td>GSGL</td>
<td>3D Graphic library using OpenGL</td>
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</table>

All developed in Kyoto U
Transport Simulation of ITER

- 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

![Graphs comparing CDBM and CDBM05 parameters and profiles.](image-url)
Turbulence transport models

Linear $+ \gamma_L/k_{\perp}^2$
- Multi Mode Model
- Weiland model

Linear $+ \text{Zonal Flow}$
- Gyrokinetic models
- Fluid models

Linear $+ \text{ZF+NL Sim}$
- GLF23 (ITG, TEM)

Self-sustained Turbulence
- CDBM

Gyrokinetic simulation
- Particle simulation
- Vlasov simulation
Improved Confinement

- Reduction of $D$
- Steepening of $n$ profile
- Steepening of $p_e$ profile
- Steepening of $p_i$ profile
- Steepening of $V_\phi$ profile
- Change of $V_\phi$ profile
- Increase of $J_{BS}$
- Increase of $\alpha$
- Increase of $E_r$
- Increase of ExB rotation shear
- Increase of Shafranov shift
- Decrease of magnetic shear
- Reduction of $X_e$
- Reduction of $X_i$
- Reduction of $\mu$
- Decrease of $T_e$ profile
- Increase of $T_i$ profile
- Increase of $V_\phi$ rotation shear

Suppression of turbulence
CDBM05 Transport Model

**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*  
$s \equiv \frac{r}{q} \frac{dq}{dr}$

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

*Elongation*  
$\kappa \equiv b/a$

*$E \times B$ rotation shear*  
$\omega_{E1} \equiv \frac{r^2}{sv_A} \frac{d}{dr} \frac{E}{rB}$

**Weak and negative magnetic shear,**  
Shafranov shift, elongation,  
and *$E \times B$ rotation shear*  
reduce thermal diffusivity.
Quasi steady-state operation of ITER

- $I_p = 6 \rightarrow 9 \text{ MA for } 10 \text{ s } P_{\text{NB}} = 19 \text{ MW on-axis}, \quad P_{\text{LH}} = 25 \text{ MW off-axis}$

- $R = 6.34 \text{ m}$
- $a = 1.859 \text{ m}$
- $\kappa = 1.857$
- $\delta = 0.434$
- $B_\phi = 5.3 \text{ T}$
- $I_p = 6 \text{ MA } \rightarrow \quad I_p = 9 \text{ MA}$
- $n_{c,\text{D,T,He}} = 0.6, 0.27, 0.27, 0.03 \text{ m}^{-3} \text{ on-axis}$
- NBI: same condition except $P_{\text{NB}} = 19 \text{ MW}$
- LHRF
  - Position of deposition: $r = 0.837 \text{ m}$
  - Width of deposition profile: $r_W = 0.8 \text{ m}$
  - Tangential radius: $r_T = 6.2 \text{ m}$
  - Parallel refractive index: $N_\parallel = 2.0$
  - Total power: $P_{\text{LH}} = 25\text{ MW}$
Full Wave Analysis: TASK/WM

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

- Boundary-value problem of **Maxwell’s equation**
  \[ \nabla \times \nabla \times E = \frac{\omega^2}{c^2} \vec{\epsilon} \cdot E + i \omega \mu_0 j_{\text{ext}} \]

- **Kinetic dielectric tensor**: $\vec{\epsilon}$
  - Wave-particle resonance: $Z[(\omega - n\omega_c)/k_{||}v_{\text{th}}]$
  - Fast ion: Drift-kinetic
    \[ \left[ \frac{\partial}{\partial t} + v_{\parallel} \nabla_{\parallel} + (v_d + v_E) \cdot \nabla + \frac{e_\alpha}{m_\alpha} (v_{\parallel} E_{\parallel} + v_d \cdot E) \frac{\partial}{\partial \varepsilon} \right] f_\alpha = 0 \]

- 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
Analysis of Alfvén Eigenmode

Alfvén resonance

$q_{\text{min}} = 2.4$

$\rho$

$0.0$ $0.2$ $0.4$ $0.6$ $0.8$ $1.0$ $1.2$

$f$ [MHz]

$0.00$ $0.05$ $0.10$

$q_{\text{min}} = 2.5$

$\rho$

$0.0$ $0.2$ $0.4$ $0.6$ $0.8$ $1.0$ $1.2$

$f$ [MHz]

$0.00$ $0.05$ $0.10$

$q_{\text{min}} = 2.6$

$\rho$

$0.0$ $0.2$ $0.4$ $0.6$ $0.8$ $1.0$ $1.2$

$f$ [MHz]

$0.00$ $0.05$ $0.10$

Higher freq.

$q_{\text{min}} = 2.4$ $f = 46.1$ kHz

$m = -2$ $m = -3$

Lower freq.

$q_{\text{min}} = 2.4$ $f = 44.1$ kHz

$m = -2$ $m = -3$

TAEs

Double TAE

RSAE

Plasma Parameters

$R_0$ 3 m
$a$ 1 m
$B_0$ 3 T
$n_e(0)$ $10^{20}$ m$^{-3}$
$T(0)$ 3 keV
$q(0)$ 3
$q(a)$ 5
$\rho_{\text{min}}$ 0.5
$n$ 1

Flat density profile
Excitation by Energetic Ions

- Without EP
  - $f_r = 37.5 \text{ kHz}$
  - $m = 3$

- With EP
  - $n_T = 0 \text{ m}^{-3}$
  - $f_T = 0 \text{ MHz}$
  - $m = -2$

- With EP
  - $n_T = 3 \times 10^{16} \text{ m}^{-3}$
  - $f_T = 38.0 \text{ kHz}$
  - $f_r = 160.2 \text{ kHz}$
  - $m = 3$

- With EP
  - $n_T = 1 \times 10^{17} \text{ m}^{-3}$
  - $f_T = 37.2 \text{ kHz}$
  - $f_r = 1858.6 \text{ Hz}$
  - $m = 3$
Integrated Analysis of AE in ITER

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 ($n = 1$)

$f_r = 95.95 \text{ kHz}$

$f_i = -1.95 \text{ kHz}$

Stabilization due to $q = 1$
Summary

• Analyses of burning plasmas require systematically integrated simulations which consist of a number of components describing various phenomena.
• Turbulent transport and nonlinear effects of MHD phenomena require first principle simulations which will clarify the physical mechanisms.
• The activity to develop burning plasma simulations, BPSI in Japan, is in progress based on TASK and TOPICS.