US-Japan JIFT Workshop on
Integrated Modeling
RIAM Kyushu Univ, 2005/09/13

Integrated Modeling Activities in Japan

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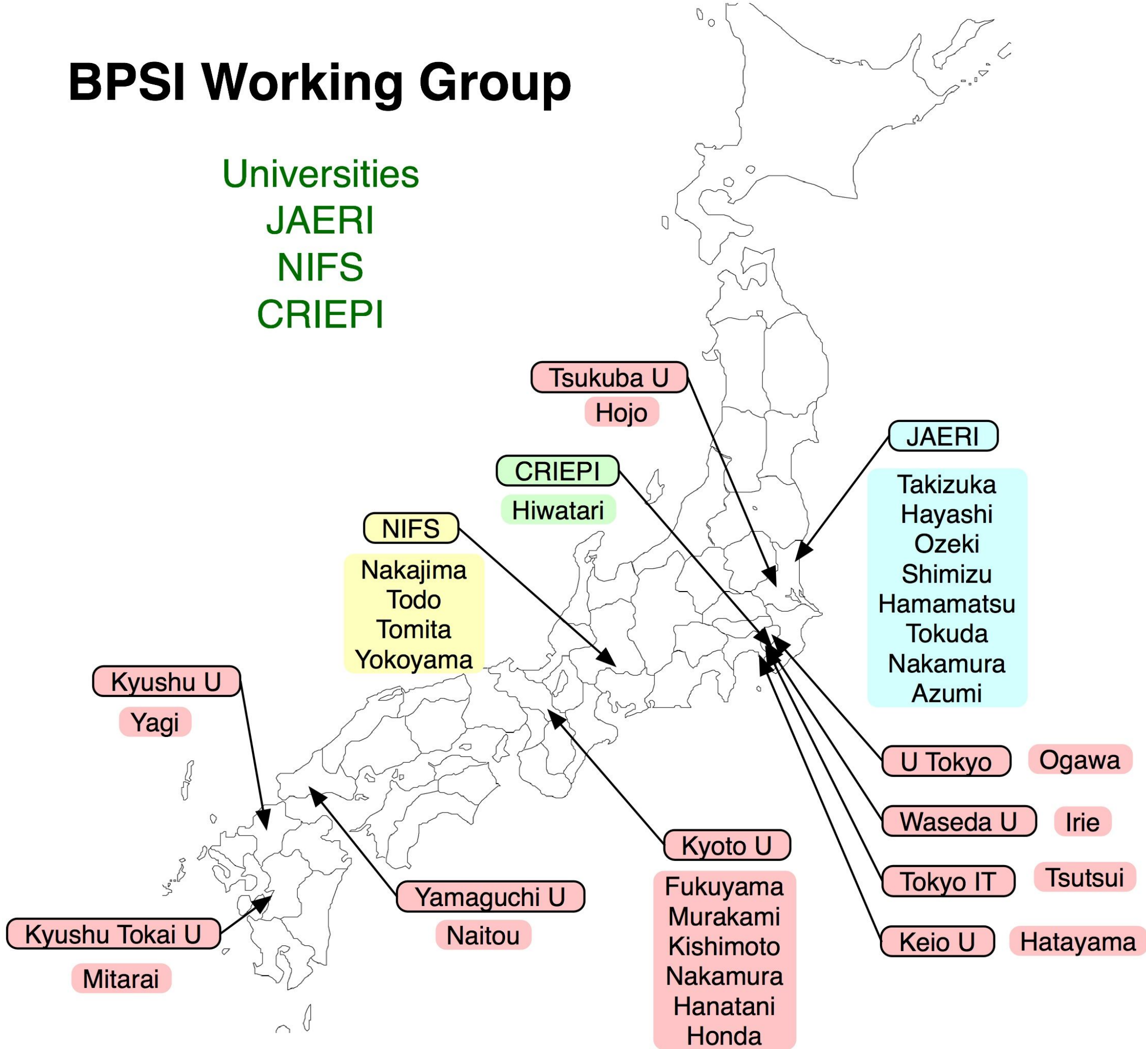
BPSI: Burning Plasma Simulation Initiative

BPSI: Research Collaboration among Universities, NIFS and JAERI

BPSI Working Group

Universities
JAERI
NIFS
CRIEPI



Targets of BPSI

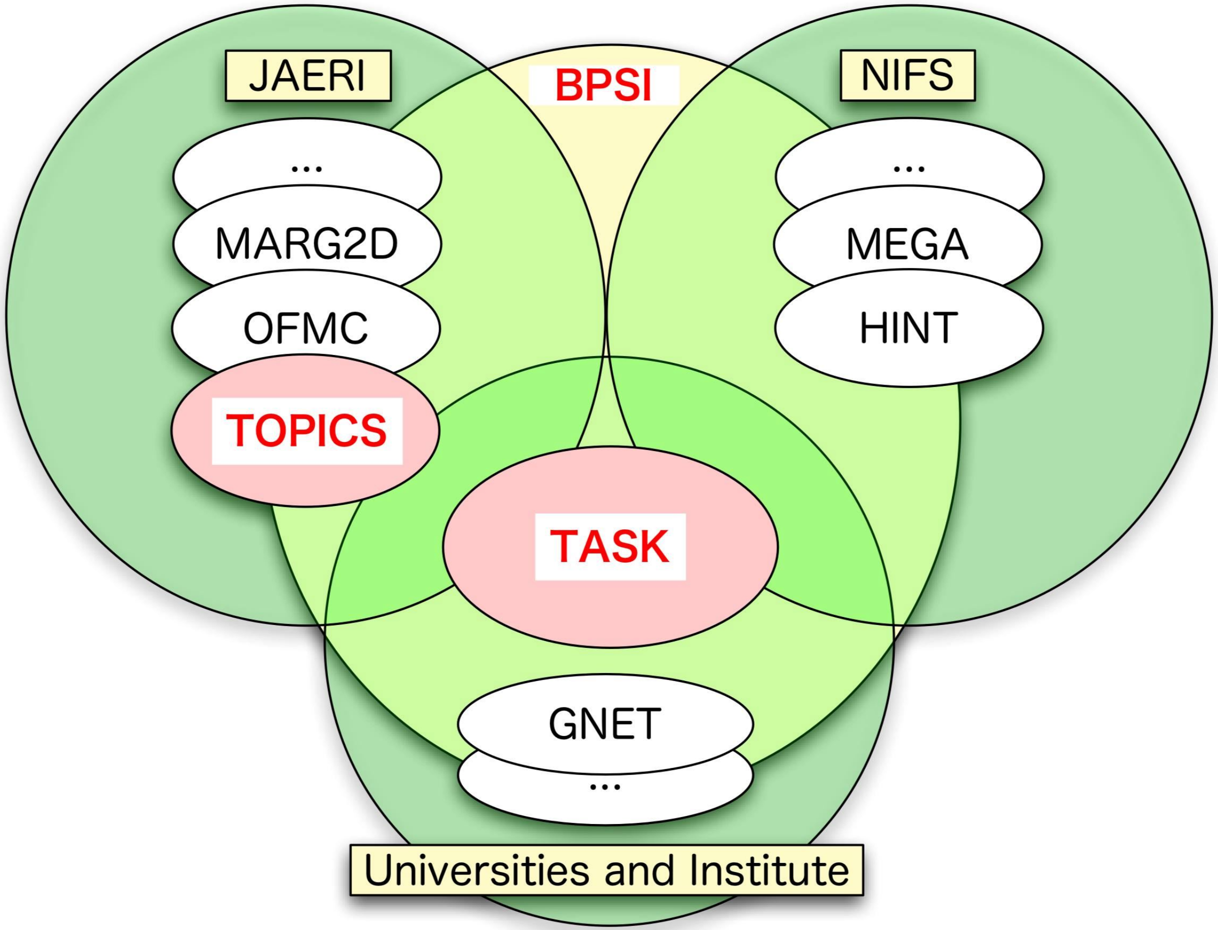
- **Framework** for integration of various plasma simulation codes
  - **Common interface**: standard data set, program interface
  - **Reference core code**: TASK
  - **Helical configuration**: data analysis and predictive simulation
- **New Modeling**: various phenomena with multi-scale physics (e.g.)
  - **Transport during and after a transient MHD events**
  - **Transport in the presence of magnetic islands**
  - **Core-SOL interface**
- **Advanced Computing**: high performance, efficient use of resources
  - **Parallel computing**: PC cluster, Massively Parallel, Vector-Parallel
  - **Distributed computing**: Globus, ITBL (IT Based Laboratory)
  - **Visualization**: Parallel visualization, VizGRID

Activities of BPSI

- **Support of Meetings**
  - Domestic workshops (supported by JSPS, RIAM, NIFS, JAERI)
  - US-Japan workshop, Korea-Japan workshop (planned)
- **Code Development**
  - **BPSI Framework**: standard dataset and interface
  - **TASK code**: (Kyoto U)
  - **Integrated code for helical plasmas**: (NIFS, Kyoto U)
  - **Intgrated code for burning plasmas**: (JAERI) by T. Ozeki
  - **Development of integrated modeling**:
    - — Transport-Turbulence-MHD by M. Yagi (Kyushu U)
    - — Core-SOL-Divertor (CRIEPI, JAERI, Tokyo U)

BPSI and TASK

TASK: Core code of BPSI for ITER, JT-60, LHD, and small machines



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 and MPI)
    — Own Graphic Libraries (gsaf, gsgl)
  - **Development using CVS** (Concurrent Version System)
    — Open Source (by 1 October 2005)

Modules of TASK

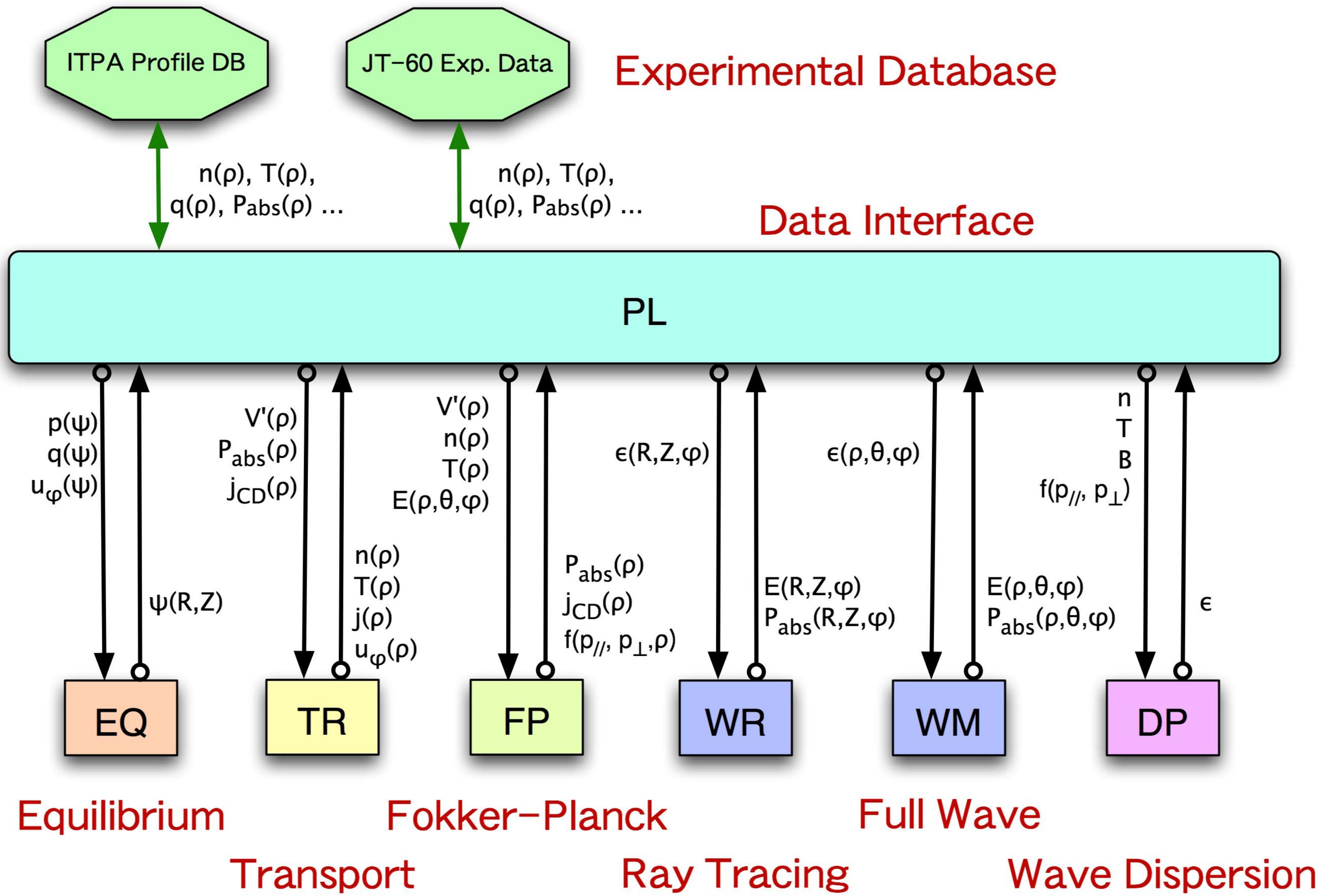
EQ	**2D Equilibrium**	Fixed boundary, Toroidal rotation
TR	**1D Transport**	Diffusive Transport, Transport models
WR	**3D Geometr. Optics**	EC, LH: Ray tracing, Beam tracing
WM	**3D Full Wave**	IC, AW: Antenna excitation, Eigen mode
FP	**3D Fokker-Planck**	Relativistic, Bounce-averaged
DP	**Wave Dispersion**	Local dielectric tensor, Arbitrary $f(v)$
PL	**Data Interface**	Data conversion, Profile database
LIB	**Libraries**	+ matrix solver, mpi interface

Associated Libraries

GSAF	2D Graphic library for X Window and EPS
GSGL	3D Graphic library using OpenGL

All developed in Kyoto U

New Modular Structure of TASK



Present Status of TASK Code

- **Core code development**
  - **Implementation of Standard Dataset and Program Interface**
  - **Development of New Modules**
    - — **EX**: 2D equilibrium with free boundary
    - — **TX**: Transport analysis based on flux-averaged fluid equation
    - — **WI**: Integro-differential wave analysis (FLR, $\boldsymbol{k} \cdot \nabla B \neq 0$)
  - **Parallel Processing using MPI Library**
  - **Extension to 3D Helical Plasmas**
- **Analysis of experiments**
  - **JT-60, LATE, TST-2, TRIAM-1M**
  - **LHD, CHS, Heliotron-J**
- **Prediction for ITER and DEMO**

Necessary Data for Integrated Modeling

- **Machine ID, Shot ID, Model ID**
- **Equilibrium Data**: e.g. EFIT
- **Plasma Status Data**
  - **Plasma Fluid Data**: Fluid quantities
  - **Plasma Kinetic Data**: Momentum distribution
  - **Electromagnetic Data**: Quasi-static $\boldsymbol{B}$, $\boldsymbol{j}$, $\boldsymbol{E}$
- **Wave Data**
  - **Wave Characteristics**: f, $\boldsymbol{k}$, Power
  - **Electromagnetic Wave Data**: $\boldsymbol{E}$, $\boldsymbol{B}$, Ray characteristics
- **Transport Data**
  - **Particle Source and Sink**: S
  - **Momentum Source and Sink**: j_{CD}, M_ϕ
  - **Power Source and Sink**: P_{OH}, P_{abs}, P_{rad}
  - **Transport Coefficients**: D, χ

Example of Data Interface (1)

- **Device data**

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} MA	Typical plasma current

- **Equilibrium data**

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	$j_{\|\|}^{\mathrm{ave}}(\rho)$	Averaged parallel current density

Example of Data Interface (2)

- **Fluid plasma data**

NSMAX	s	Number of particle species
PA	A_s	Atomic mass
PZ0	Z_s	Charge number
PZ	Z_s	Charge state number
PNR	$n(\rho)\ 10^{20}\mathrm{m}^3$	Number density
PTR	$T(\rho)\,\mathrm{keV}$	Temperature
PUR	$u_\phi(\rho)\,\mathrm{m/s}$	Toroidal rotation velocity

  - Example: **`PROF1D(NR)%SPECIES(NS)%PNR`**

- **Kinetic plasma data**

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

- **Full wave field data**

CE	$\boldsymbol{E}(\rho,\chi,\xi)$	Complex wave electric field
CB	$\boldsymbol{B}(\rho,\chi,\xi)$	Complex wave magnetic field

Data Exchange Interface in BPSI

- **Language**
  - **Fortran95**: Derived type data, Module inheritance, Namelist
- **Data category**
  - **Predefined Data**
  - **Additional Data**
- **Data manipulation**
  - **Specify data**: machine, shot, model, time
  - **Acquire data**: 0D, 1D(ρ), 2D(ρ,χ), 2D(R,Z), 0D(t), 1D(ρ,t), 2D(ρ,χ,t), 2D(R,Z,t),
  - **Change data**: 0D, 1D(ρ), 2D(ρ,χ), 2D(R,Z)
  - Define data
  - Save data in file
  - Load data from file
  - Plot data

Execution Control Interface in BPSI (1)

- **Example for TASK/TR**

TR_INIT	Initialization (Default value, Read file)	BPSM_INIT('TR')
TR_PARM(PSTR)	Parameter setup (Namelist input)	BPSM_PARM('TR',PSTR)
TR_PROF(T)	Profile setup (Spatial profile, Time)	BPSM_PROF('TR',T)
TR_EXEC(DT)	Exec one step (Time step)	BPSM_EXEC('TR',DT)
TR_GOUT(PSTR)	Plot data (Plot command)	BPSM_GOUT('TR',PSTR)
TR_SAVE	Save data in file	BPSM_SAVE('TR')
TR_LOAD	load data from file	BPSM_LOAD('TR')
TR_TERM	Termination	BPSM_TERM('TR')

Development of Integrated Simulation System for Helical Plasmas

Presented by
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Background & Objectives

Recent progress of computers (parallel/vector-parallel computers, PC clusters, for example) and numerical codes for helical plasmas like three-dimensional MHD equilibrium codes, combined with the development of the plasma diagnostics technique, enable us to do the detailed theoretical analyses of the individual experimental observations.

It is pointed out that the experimental data analysis from the viewpoints of integrated physics is an important issue to understand the confinement physics globally.

↓

To do that, the development of the integrated simulation system which has a modular structure and user-friendly interfaces is necessary.

The integrated numerical simulation will also be a good help to draw up new experimental plans. In this study, we have started the development of such a system.

Outline of the Integrated Simulation System

1) The integrated simulation system to be developed has a modular structure which consists of modules for calculating MHD equilibrium/stability, transport and heating.

2) Each module can be selected in accordance with a user's request and can be combined with other modules.

3) In order to maintain the independence of each module, which is an independent and complete program, sequences of the integrated simulation are controlled by a shell or script (perl or ruby, for example).

4) Since some modules are suitable for running on the vector machine and others are on the PC cluster, we are going to develop a module-by-module distributed computing system through the network.

Current status

Up to now, we have reviewed the modeling and the specifications of interfaces between modules, and developed MHD equilibrium code HINT2 and bootstrap current calculation code BSC. The HINT2 is a revised code of the HINT and coded using Fortran 90. It is used for calculating accurate MHD equilibrium of LHD including peripheral ergodic region.

Transport module

When we want to perform the integrated simulation during the entire plasma duration, a transport module is to be a core module. An integrated tokamak transport code, TASK, which is a core code for BPSI (Burning Plasma Simulation Initiative; research collaboration among universities, NIFS and JAERI in Japan) activity, will be extended for the helical configuration and used as a transport module.

TASK/HT module

Current Plan

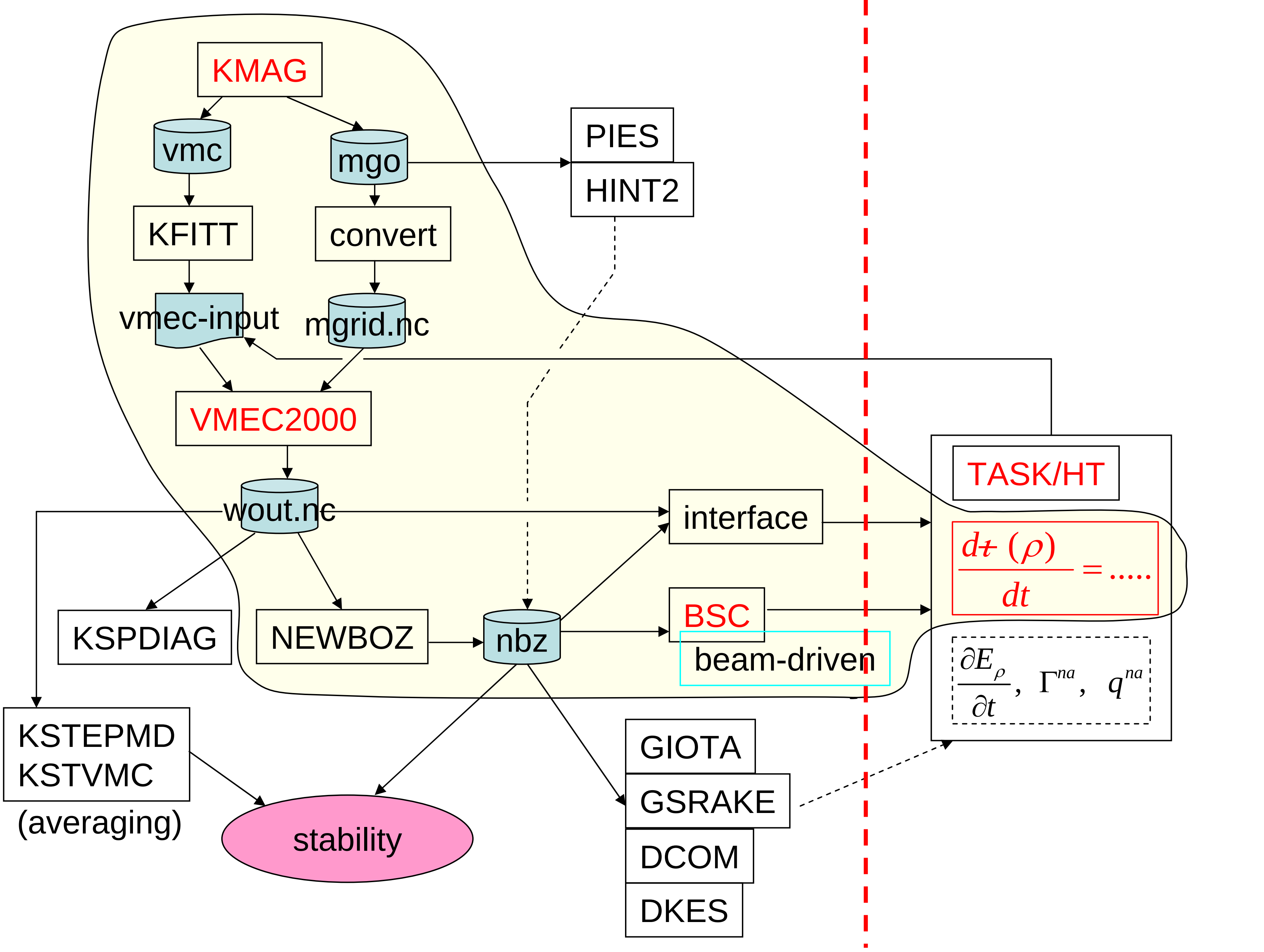
Though almost all transport simulations done for LHD plasmas have neglected the net toroidal current, finite net plasma current has been observed in actual LHD experiments.

It is considered that the bootstrap current and the beam driven current are included in it, but it is difficult to estimate fraction of these components accurately because plasmas are not stationary in many cases.

So, as the first step of the extension of the TASK, time evolution of the plasma net current, which is consistent with the three-dimensional MHD equilibrium (by VMEC), will be solved for LHD plasmas by using time evolution of density and temperature profiles obtained by the experiment and taking into account of the bootstrap current and the beam-driven current.

In order to calculate the bootstrap current, we have developed the BSC code, which is suitable for the usage as a module, by improving SPBSC code. The BSC code has been applied to the analysis of the bootstrap current observed in Heliotron J plasmas. It is shown that the neoclassical transport theory can explain the experimental observation that the bumpy field component can change the direction of the bootstrap current.

We will compare the result to the experimental data, and the knowledge obtained by the comparison will be used for code development as a feedback.



KMAG
vmc
mgo
PIES
HINT2
KFITT
convert
vmec-input
mgrid.nc
VMEC2000
wout.nc
interface
TASK/HT
$\frac{d\tau(\rho)}{dt} = ...$
BSC
beam-driven
$\frac{\partial E_\rho}{\partial t}, \Gamma^{na}, q^{na}$
KSPDIAG
NEWBOZ
nbz
KSTEPMD
KSTVMC
(averaging)
stability
GIOTA
GSRAKE
DCOM
DKES

BSC code

bootstrap current in low collisionality regime

K.C. Shaing, B.A. Carreras, et al., Phys. Fluids **B1** (1989) 1663.

linearized drift-kinetic equation

$$v_\parallel \hat{n}\cdot\nabla f_j + \mathbf{v}_{dj}\cdot\nabla\psi \frac{\partial f_{Mj}}{\partial\psi} = C_j(f_j) ,$$

lowest order:

$$v_\parallel \hat{n}\cdot\nabla f_j^{(0)} + \mathbf{v}_{dj}\cdot\nabla\psi \frac{\partial f_{Mj}}{\partial\psi} = 0 .$$

$$f_j^{(0)} = -\frac{v_\parallel}{\Omega_j} H_1 \frac{\partial f_{Mj}}{\partial\psi} - v_\parallel \frac{cM_j}{e_j} \frac{G+\iota I}{2B_0^2\iota} B H_2 \frac{\partial f_{Mj}}{\partial\psi} - v \frac{cM_j}{e_j} B_M \frac{G+\iota I}{2B_0^2\iota} q\tilde{h} \frac{\partial f_{Mj}}{\partial\psi} + g_j(\psi) ,$$

magneto-differential equation for $\tilde{h}$ ⇨ $\tilde{h}$

next order: $v_\parallel \hat{n}\cdot\nabla f_j^{(1)} = C_j(f_j^{(0)}) ,$

flux surface average ⇨ integration constant $g_j(\psi)$

$$g_j = \frac{2H(1-\lambda)V_\parallel(A_0 L_0^{(3/2)} + A_1 L_1^{(3/2)} + \cdots)}{v_{tj}^2} f_{M_j} + \frac{cM_j}{e_j} v B_M \frac{G+\iota I}{B_0^2\iota} q \frac{\partial f_{M_j}}{\partial\psi} H(1-\lambda)\sigma \times \sum_{n,m}{}' \int_\lambda^1 d\lambda \frac{d\lambda}{\langle |v_\parallel|/v\rangle} \left\langle \frac{|v_\parallel|}{v} \left(\frac{mR+nS}{m-nq} \frac{\partial\alpha_{nm}}{\partial\lambda} + \frac{m+nq}{2q(m-nq)} \frac{\partial\beta_{nm}}{\partial\lambda} \right) \left[e^{i(n\phi-m\theta)} - e^{i(n\phi_M - m\theta_M)} \right] \right\rangle$$

parallel momentum balance
parallel heat flux balance

$$\langle \mathbf{B}\cdot\nabla\cdot\boldsymbol{\pi}_e\rangle = \langle BF_{1e}\rangle ,$$
$$\langle \mathbf{B}\cdot\nabla\cdot\boldsymbol{\Theta}_e\rangle = \langle BF_{2e}\rangle ,$$
$$\langle \mathbf{B}\cdot\nabla\cdot\boldsymbol{\pi}_i\rangle = \langle BF_{1i}\rangle ,$$
$$\langle \mathbf{B}\cdot\nabla\cdot\boldsymbol{\Theta}_i\rangle = \langle BF_{2i}\rangle ,$$

$$\langle BJ_{\parallel}\rangle_b = \langle BNe(U_{\parallel i} - U_{\parallel e})\rangle$$

BS current

G_{bs}

$$\langle BJ_{\parallel}\rangle_b = -\sigma_{\text{eff}}(M_e\nu_e/Ne^2)(f_t/f_c)c\tilde{G}_b\mu_{1e}\Bigg[\left(1+\frac{l_{12}^{eb}}{l_{22}^{eb}}\frac{\mu_{2e}}{\mu_{1e}}\right) \times\left(P' + NT_i'\frac{l_{22}^{i}\mu_{2i}}{|\mu_i|\nu_i NM_i f_t/f_c + l_{22}^{i}\mu_{1i}}\right) + \frac{\mu_{2e}}{\mu_{1e}}\left(1+\frac{l_{12}^{eb}}{l_{22}^{eb}}\frac{\mu_{3e}}{\mu_{2e}}\right)NT_e'\Bigg], \quad (33)$$

geometrical factor G_{bs}

$$G_{bs} = \langle H_1\rangle + \frac{H_2}{2}\frac{I+qG}{B_0^2}\langle B^2\rangle - \frac{3}{4}\frac{q}{f_t}\frac{I+qG}{B_0^2}\langle B^2\rangle\int_0^1\frac{\lambda W(\lambda)\mathrm{d}\lambda}{\langle(1-\lambda B/B_{max})^{1/2}\rangle} \quad (14)$$

where

$$\lambda \equiv \mu B_{max}/\tfrac{1}{2}m_j v^2,\ |v_\parallel|/v = (1-\lambda B/B_{max})^{1/2}$$

$q = 1/\iota$ is the safety factor and

$$\langle H_1\rangle = \frac{q}{2}\left(G - \frac{I}{q}\right),$$
$$H_2 = [\langle(\partial B/\partial\theta)^2\rangle - q^2\langle(\partial B/\partial\zeta)^2\rangle]/\langle(\partial B/\partial\theta + q\partial B/\partial\zeta)^2\rangle$$

G_{bs} is calculated only by G, I, q
and Fourie spectrum of B, B_{nm}
in the Boozer coordinates

asymmetric term
(effect of boundary layer)

$$W(\lambda) = \sum_{(n,m)\neq(0,0)}\frac{nR+mS}{n-mq}\Bigg\{-2\frac{\partial\alpha_{nm}}{\partial\lambda} \times\left\langle\frac{|v_\parallel|}{v}\exp[-\mathrm{i}(n\theta_B - m\zeta_B)]\right\rangle + \frac{1}{f_c}\frac{\langle B^2\rangle}{B_{max}^2} \times \exp[\mathrm{i}(n\theta_{max} - m\zeta_{max})]\left(\frac{3}{2}\alpha_{nm}(\lambda=1) + d_{nm}\right) + \frac{1}{2q}\frac{nR+mS}{n-mq}\Bigg[-2\frac{\partial\beta_{nm}}{\partial\lambda}\left\langle\frac{|v_\parallel|}{v}\exp[-\mathrm{i}(n\theta_B - m\zeta_B)]\right\rangle + \frac{1}{f_c}\frac{\langle B^2\rangle}{B_{max}^2}\exp[\mathrm{i}(n\theta_{max} - m\zeta_{max})]\left(\frac{3}{2}\beta_{nm}(\lambda=1) + e_{nm}\right)\Bigg]\Bigg\} \quad (15)$$

Time evolution of the rotational transform profile which is consistent with three-dimensional MHD equilibrium

$$\rho = \sqrt{\frac{\Phi_T}{\Phi_{Ta}(t)}}, \quad \Phi_T = \rho^2 \Phi_{Ta}(t)$$

$$\begin{aligned} S_{11} &= \frac{V'}{4\pi^2} \left\langle \frac{g_{\theta\theta}(1-\partial_\zeta \lambda) + g_{\theta\zeta}\partial_\theta \lambda}{g} \right\rangle, \\ S_{12} &= \frac{V'}{4\pi^2} \left\langle \frac{g_{\theta\zeta}}{g} \right\rangle, \end{aligned}$$

$$\begin{aligned} \frac{\partial \iota}{\partial t} &= \frac{\rho}{2}\frac{\partial \iota}{\partial \rho}\frac{\partial \ln|\Phi_{Ta}(t)|}{\partial t} \\ &+ \frac{1}{2\rho}\frac{\partial}{\partial \rho}\left\{ \frac{\eta_{||}}{2\rho \Phi_{Ta}(t)^2}\frac{\partial V}{\partial \rho}\left\{ \frac{\langle B^2 \rangle}{2\rho}\frac{\partial}{\partial \rho}\left[2\rho(S_{11}\iota + S_{12})\right] + \frac{\partial P}{\partial \rho}(S_{11}\iota + S_{12}) - \left\langle \vec{J}_s \cdot \vec{B} \right\rangle \right\}\right\} \quad (1.82) \end{aligned}$$

relation between net toroidal current and rotational transform

$$\iota = \frac{I_T}{S_{11}\Phi_T'} - \frac{S_{12}}{S_{11}},$$

Summary

- The activity of Burning Plasma Simulation Initiative in Japan is gradually increasing.
- We are developing TASK code as a reference core code for burning plasma simulation based on transport analysis.
- The TASK code is composed of modules: equilibrium, transport, wave analysis, velocity space analysis, and data interface. New modular structure is almost completed.
- Future work
  - Improvement of modules: Full modular structure
  - Standard data interface with other simulation code
  - Systematic comparison with experimental data
  - Development of new modules