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プラズマ・核融合学会 第21回年会
静岡県コンベンションアーツセンター

シンポジウム「核融合プラズマシミュレーションの進展」

磁場閉じ込めプラズマ統合コード

Integrated Simulation Code for Magnetic Confinement Fusion

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- 核燃焼プラズマ統合シミュレーション
- 核燃焼プラズマ統合コード構想：BPSI
- トロイダルプラズマ解析コード：TASK
- 今後の課題

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 & diverted & wall-plasma)
    — Whole discharge
    (startup & sustainment & transients events & termination)
    — Reasonable accuracy (comparison with experiments)
    — Reasonable computer resources (still limited)

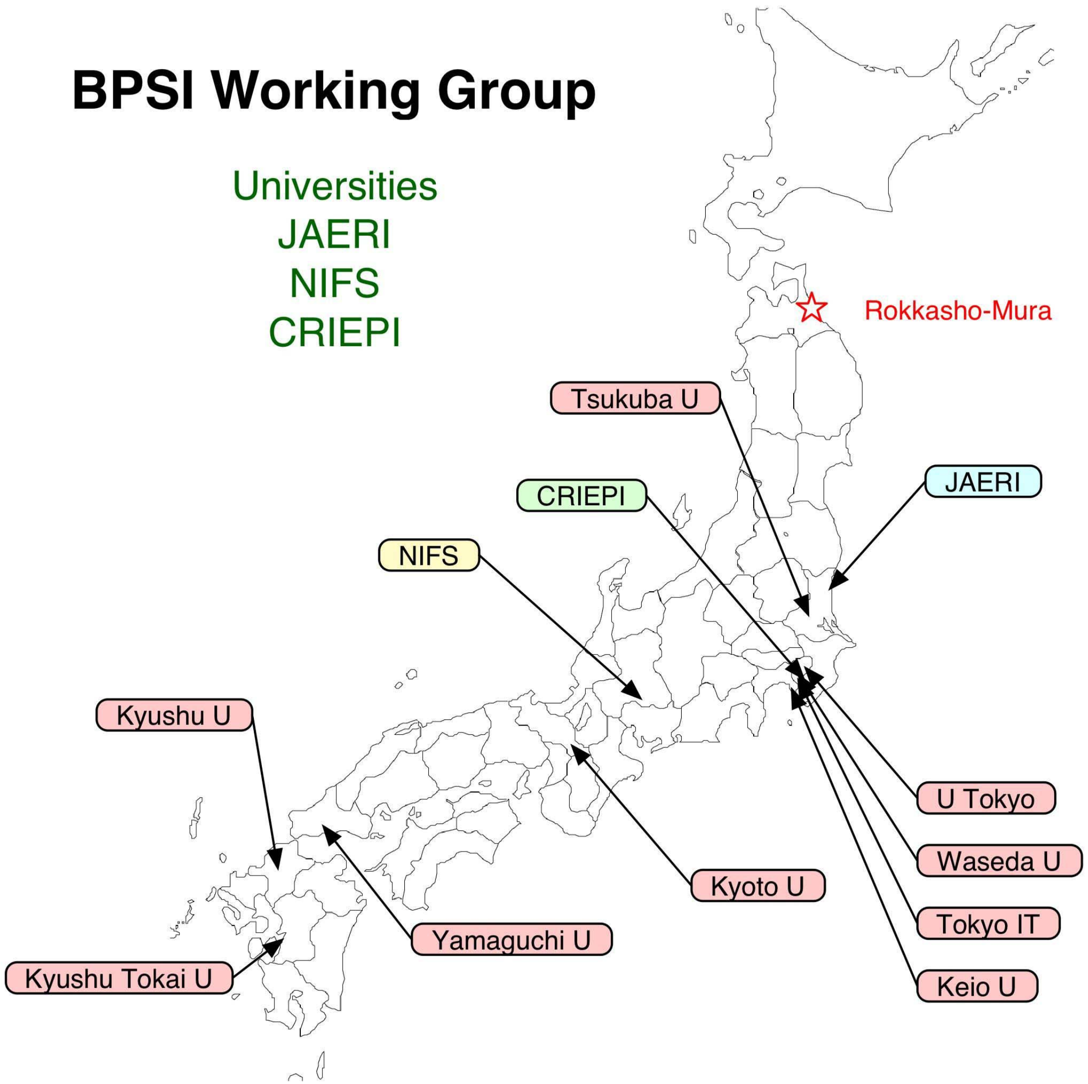
- **How can we do?**
  - Gradual increase of understanding and accuracy
  - Organized development of simulation system

BPSI: Burning Plasma Simulation Initiative

Research Collaboration among Universities, NIFS and JAERI

BPSI Working Group

Universities
JAERI
NIFS
CRIEPI



Targets of BPSI

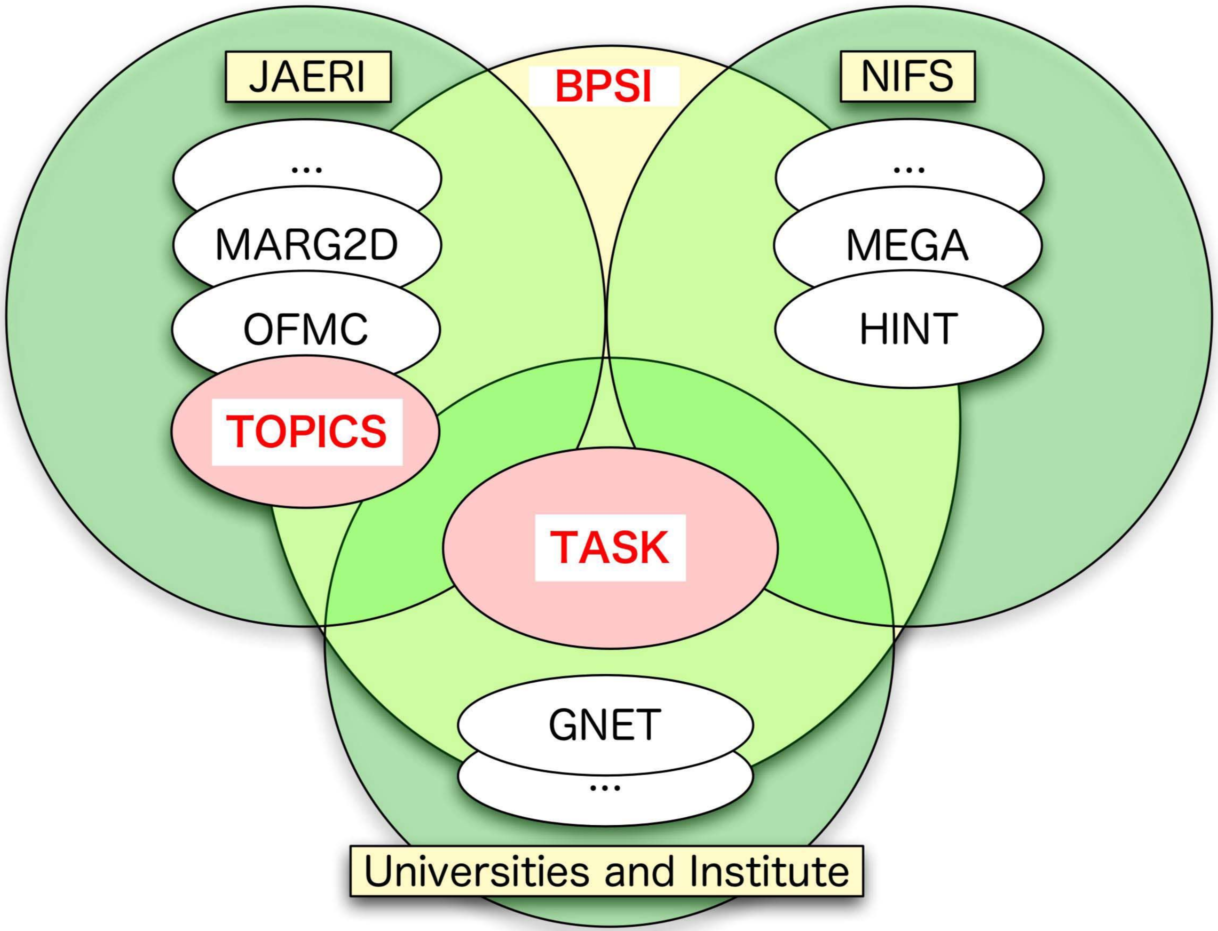
- **Framework** for collaboration of various plasma simulation codes
  - **Common interface** for data transfer and execution control
  - **Standard data set** for data transfer and data storage
  - **Reference core code**, TASK
  - **Helical configuration** included
- **Physics Integration** of phenomena 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, Massively Parallel, Vector-Parallel
  - **Distributed computing**: GRID computing, Globus, ITBL
  - **Visualization**: Parallel visualization, VisiGRID

Status of BPSI

- 1st Stage
  - Development of standard dataset and module interface
  - Integrated simulation of multi-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

Structure of BPSI

TASK: Core code of BPSI for ITER, JT-60, LHD, and small machines
TOPICS: Transport Analysis and Predictive Simulation for JT-60



Similar Activities in US

- **NTCC** (National Transport Code Collaboration)
  - Transport code, Module library
- **SciDAC** (Scientific Discovery through Advanced Computing)
  - Plasma Microturbulence Project
  - Extended MHD Modeling
  - Wave-Particle Interaction
  - National Fusion Collaboratory
  - Computational Atomic Physics
  - Magnetic Reconnection

- **Fusion Simulation Project**: 2005 – 2019
  - **A Production Component**: including Integrated Plasma Simulator
  - **A Research and Integration Component**:
    3D first principles simulation, Focused integration
  - **A Software Infrastructure Component**:
    communication, visualization, experimental database

Similar Activities in EU

- **EFDA Task Force: Integrated Transport Modelling** (Dec. 2003)
  - `http://www.efda-taskforce-itm.org/`
- **Integrated Modelling**
  - Physics integration
  - Code integration
  - Discipline integration: Theorist/Modeller/Computer Scientist/Experimentalist
- **Projects**
  - The Code Platform Project (CPP)
  - The Data Coordination Project (DCP)
  - Five Integrated Modelling Projects (IMPs)
    - — Equilibrium and linear MHD stability
    - — Non-linear MHD and disruptions
    - — Transport code and discharge evolution
    - — Transport processes and micro-stability
    - — Heating, current drive and fast particles

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 the end of 2004)
  - **Parallel Processing using MPI Library**
  - **Extension to Toroidal Helical Plasmas**

Modules of TASK

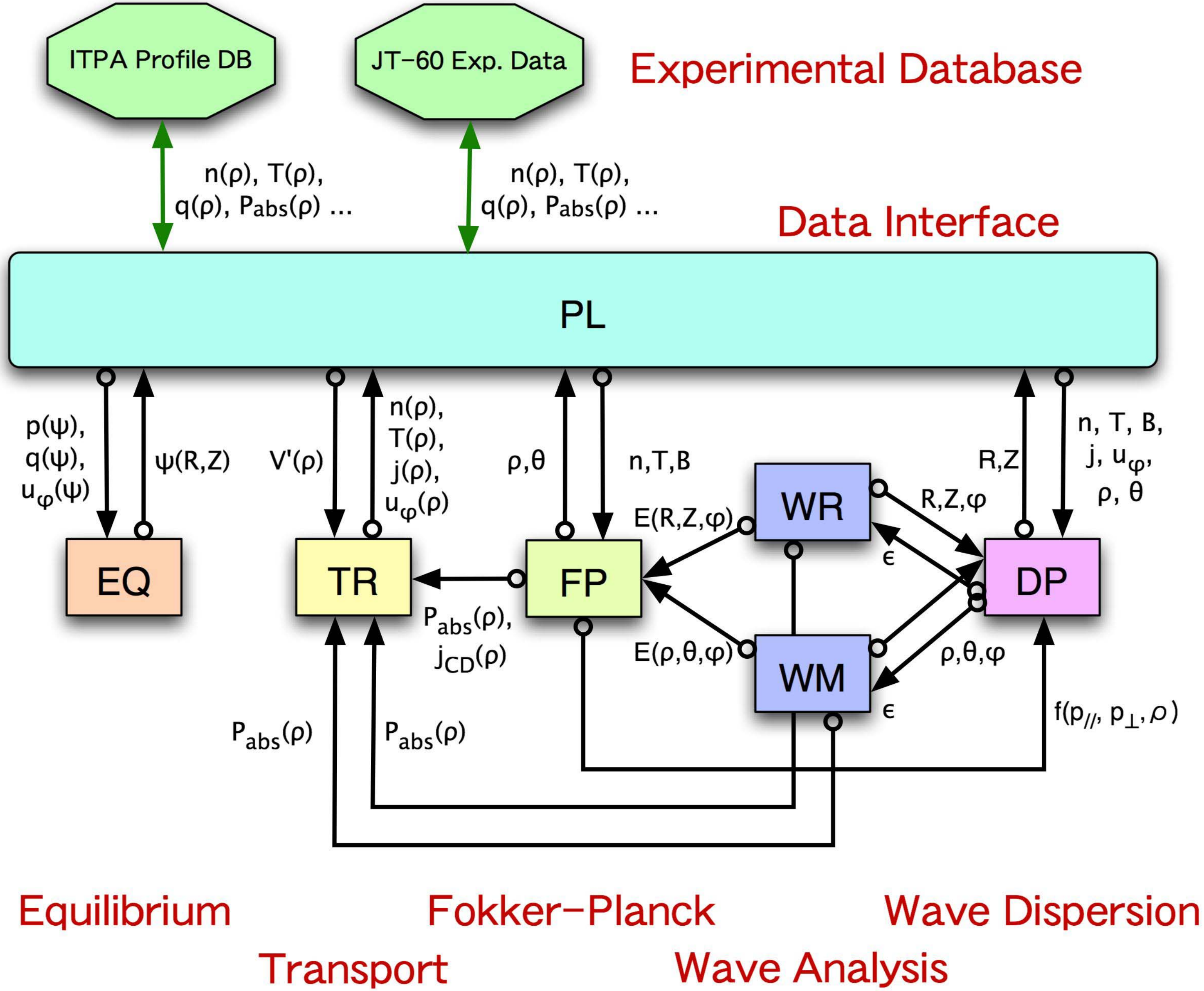
EQ	**2D Equilibrium**	**Fixed boundary, Toroidal rotation**
TR	**1D Transport**	**Diffusive Transport, Transport models**
WR	**3D Geometr. Optics**	**EC, LH: Ray tracing, Beam tracing**
WM	**3D Full Wave**	**IC, AW: Antenna excitation, Eigen mode**
FP	**3D Fokker-Planck**	**Relativistic, Bounce-averaged**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

Associated Libraries

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

All developed in Kyoto U

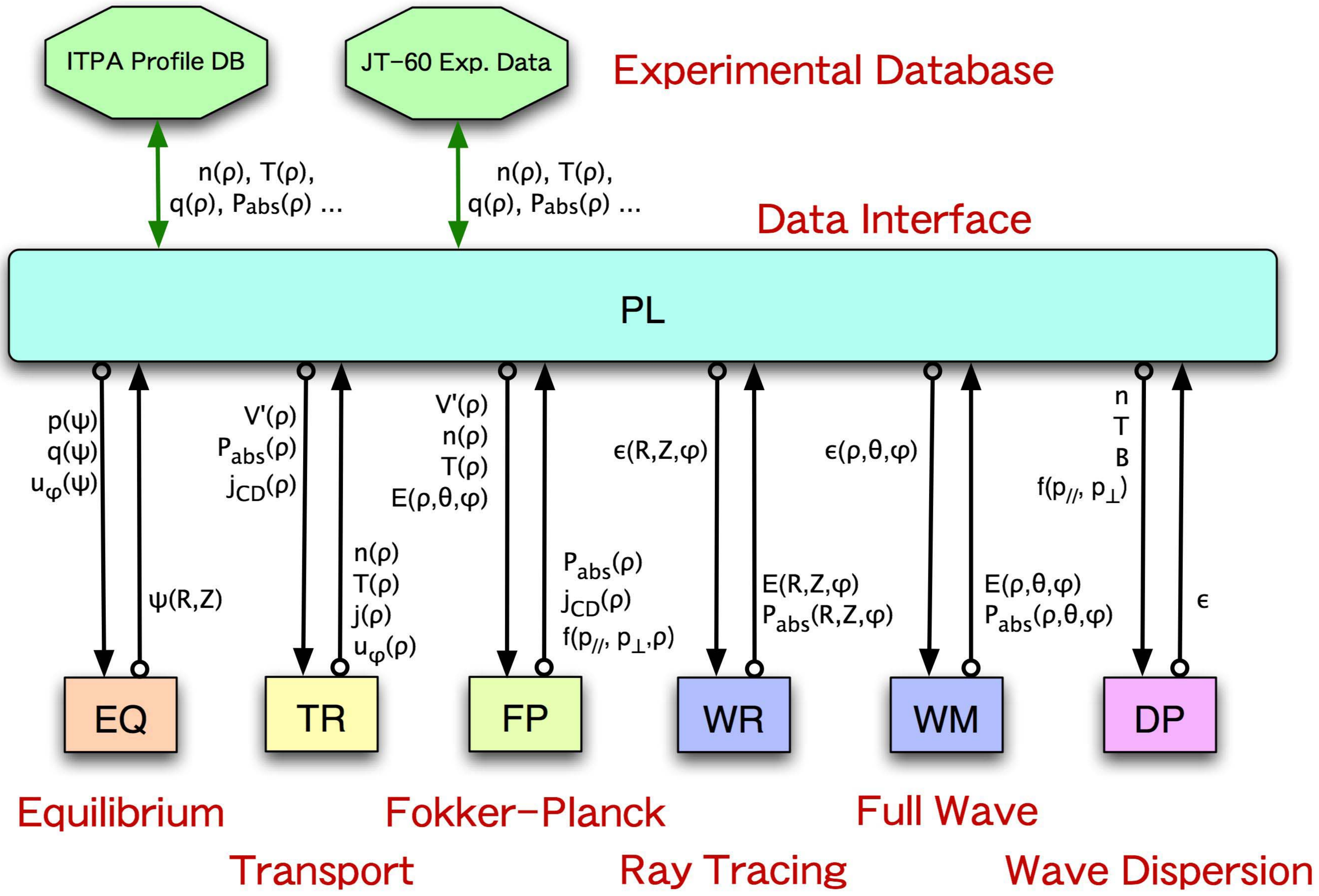
Present Structure of TASK



Under Development

- **New Modules**
  - **EX**: 2D equilibrium with free boundary
  - **TX**: Transport analysis based on flux-averaged fluid equation
  - **WA**: Global linear stability analysis
  - **WI**: Integro-differential wave analysis (FLR, $k \cdot \nabla B \neq 0$)
- **Extension to 3D Helical System**
  - **3D Data Structure**
  - **3D Equilibrium**: VMEC, HINT
  - **Wave Analysis**: Already 3D
  - **Transport Analysis**: New transport model
- **New Modular Structure**

New Modular Structure of TASK



ECCD analysis : TASK/WR/FP/DP

Geometrical Optics: TASK/WR

- **Ray Tracing Method:**
  - Plane wave: beam size $d \gg$ Wave length λ
  - 6 Ordinary Differential Equations for r_α, k_α,
- **Beam Tracing Method**
  - Analysis of wave propagation with finite beam size
  - Beam shape : Gaussian beam
  - 18 Ordinary Differential Equations for r_α, k_α, $s_{\alpha\beta}$ and $\phi_{\alpha\beta}$

— Curvature radius: $R_\alpha = 1/\lambda s_{\alpha\alpha}$,

— Beam radius: $d_\alpha = \sqrt{2/\phi_{\alpha\alpha}}$

Fokker-Planck Analysis : TASK/FP

- **Fokker-Planck equation**

  for velocity distribution function $f(p_{\|}, p_{\perp}, \psi, t)$

$$\frac{\partial f}{\partial t} = E(f) + C(f) + Q(f) + L(f)$$

  - $E(f)$: 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

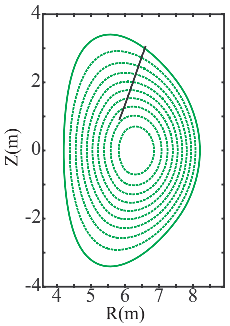
- **Bounce-averaged**: Trapped particle effect, zero banana width
- **Relativistic**: momentum p, weakly relativistic collision term
- **Nonlinear collision**: momentum or energy conservation
- **Three-dimensional**: spatial diffusion (neoclassical, turbulent)

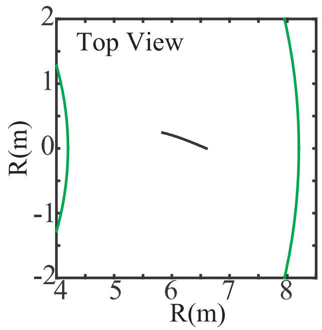
Wave Dispersion Analysis : TASK/DP

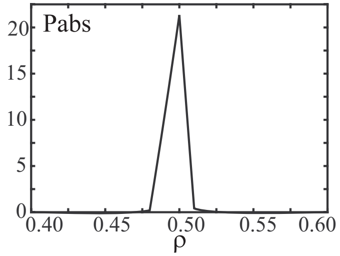
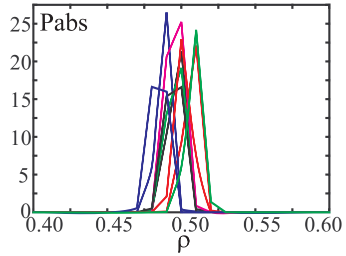
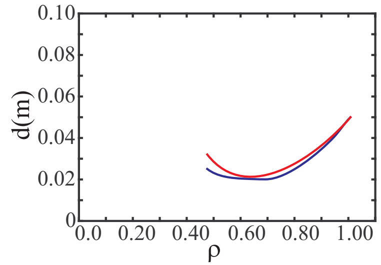
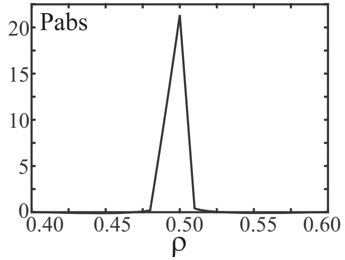
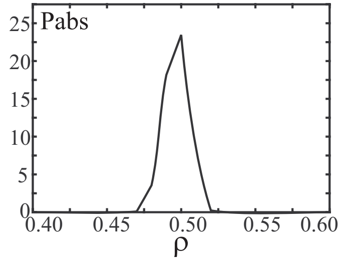
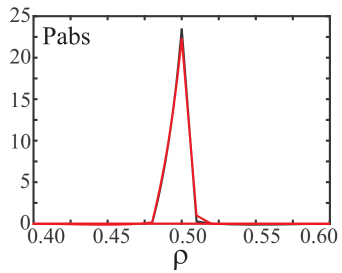
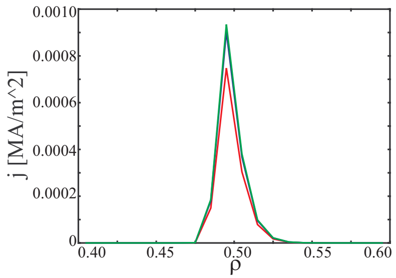
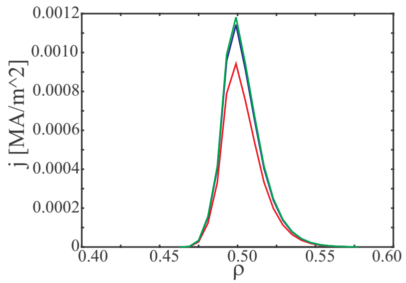
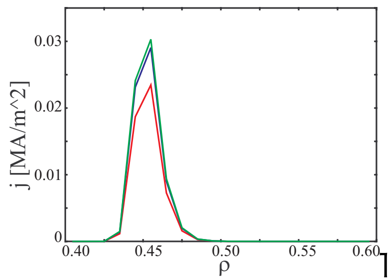
- **Various Models of Dispersion Tensor $\overleftrightarrow{\epsilon}(\omega, \boldsymbol{k}; \boldsymbol{r})$:**
  - **Resistive MHD model**
  - **Collisional cold plasma model**
  - **Collisional warm plasma model**
  - **Kinetic plasma model (Maxwellian, non-relativistic)**
  - **Kinetic plasma model (Arbitrary $f(\boldsymbol{v})$, relativistic)**
  - **Gyro-kinetic plasma model (Maxwellian, non-relativistic)**
  - **Gyro-kinetic plasma model (Arbitrary $f(\boldsymbol{v})$, non-relativistic)**
- **Arbitrary $f(\boldsymbol{v})$:**
  - **Relativistic Maxwellian**
  - **Output of TASK/FP**

Analysis of ECCD by TASK Code

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





	One Ray	Multi Rays	Beam Tracing
Ray/Beam Profile			
P_{abs} **Profile**			
j_{CD} **Profile**			

Full wave analysis: TASK/WM

- **magnetic surface coordinate**: (ψ, θ, φ)
- **Boundary-value problem of Maxwell's equation**

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

- **Kinetic dielectric tensor**: $\overleftrightarrow{\epsilon}$
  - **Wave-particle resonance**: $Z[(\omega - n\omega_{\mathrm{c}})/k_{\|} v_{\mathrm{th}}]$
  - **Fast ion: Drift-kinetic**

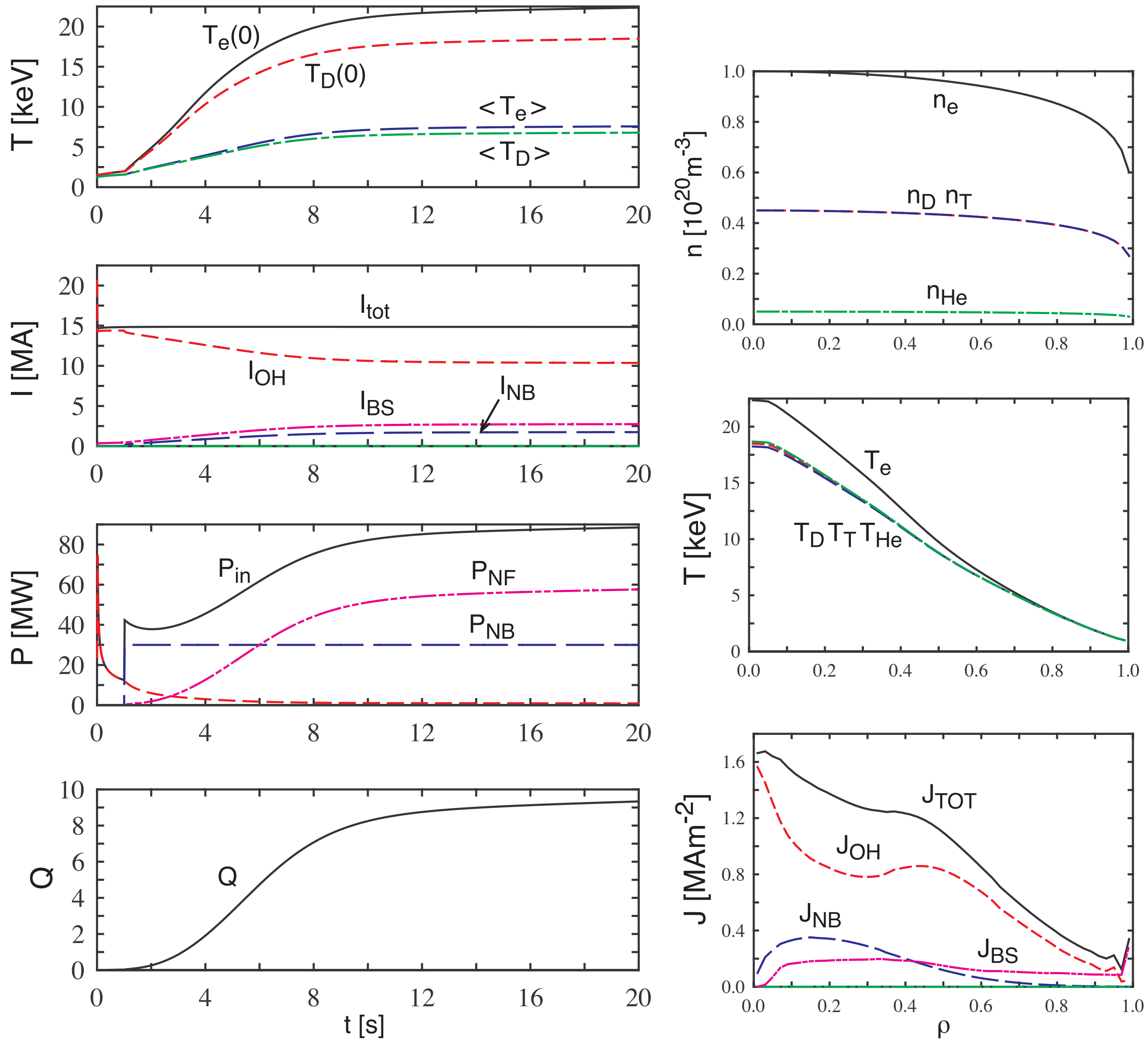
$$\left[\frac{\partial}{\partial t} + v_{\|}\nabla_{\|} + (\boldsymbol{v}_{\mathrm{d}} + \boldsymbol{v}_{\mathrm{E}}) \cdot \nabla + \frac{e_\alpha}{m_\alpha}(v_{\|}E_{\|} + \boldsymbol{v}_{\mathrm{d}} \cdot \boldsymbol{E})\frac{\partial}{\partial \varepsilon}\right] f_\alpha = 0$$

- **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**

Diffusive Transport Analysis: TASK/TR

- **Transport Equation Based on Gradient-Flux Relation**
  - **Multi thermal species**: e.g. Electron, D, T, He
    — Density, thermal energy, (toroidal rotation)
  - **Two beam components**: Beam ion, Energetic α
    — Density, toroidal rotation
  - **Neutral**: Two component (cold and hot), Diffusion equation
  - **Impurity**: Thermal species or fixed profile
- **Transport Model**
  - **Neoclassical**: Wilson, Hinton & Hazeltine, Sauter, NCLASS
  - **Turbulent**: CDBM (current diffusive ballooning mode), GLF23 (V1.61), IFS/PPPL, Weiland
- **Interface to Experimental Data**
  - UFILE (ITPA profile DB)

ITER Standard Operation (Preliminary)



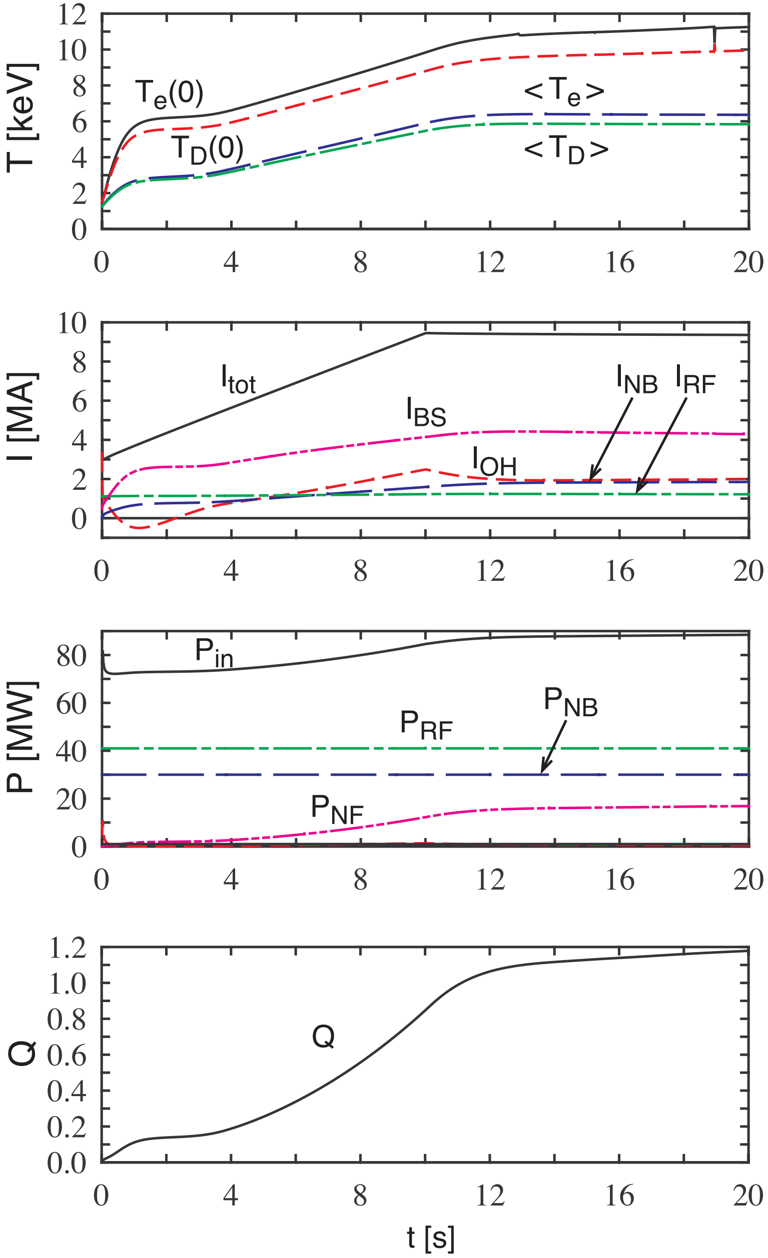
$I_p = 15\,\mathrm{MA}$

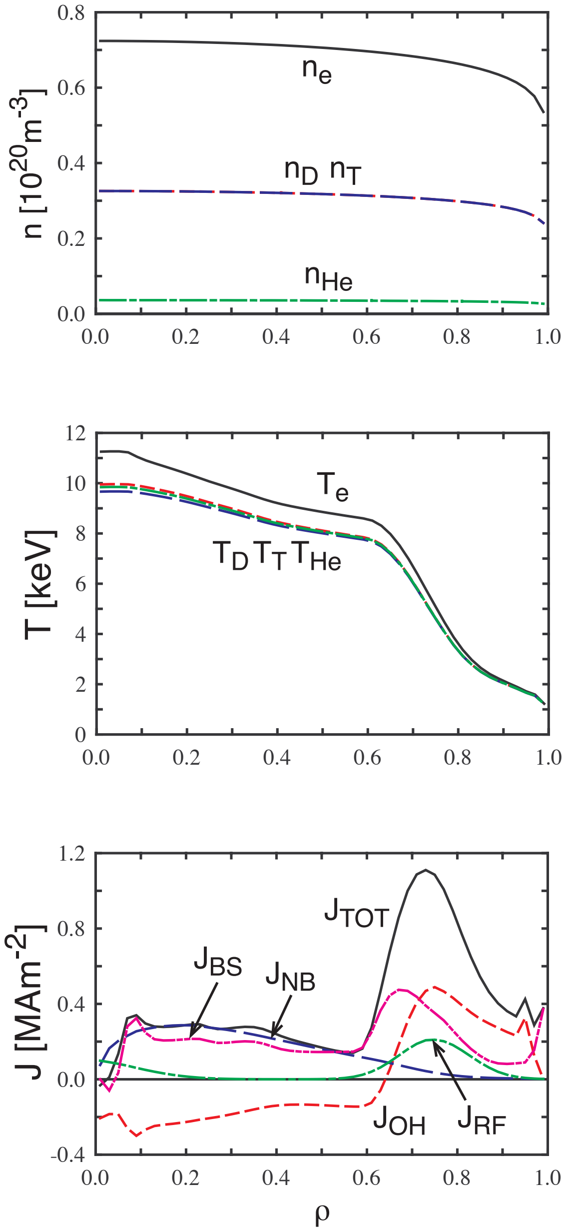
$P_{NB} = 30\,\mathrm{MW}$

$Q = 9.1$

(Preliminary)

ITER Steady State Scenario (Preliminary)





$I_p = 9\,\mathrm{MA}$

$P_{NB} = 30\,\mathrm{MW}$

$P_{LH} = 20\,\mathrm{MW}$

$P_{IC} = 20\,\mathrm{MW}$

$P_{EC} = 2\,\mathrm{MW}$

$Q = 1.2$

(Preliminary)

Summary

- We have started Burning Plasma Simulation Initiative in Japan as a research collaboration among universities, NIFS and JAERI.
- We are developing an integrated modeling code TASK as a reference core code of BPSI.
- Our present targets are
  - Development of standard dataset and module interface
  - Development of the core code TASK with New modular structure
  - Module validation with experimental results
  - Code collaboration between TOPICS and TASK
  - Extension to the 3D helical configuration
  - Promotion of BPSI activities to experimentalists
- We are discussing with the EU and US initiatives on the international collaboration of code exchange and benchmark test.

Background

- **Experiments: Significant Progress in Diagnostics**
  - **High resolution in space and time**
  - **Electromagnetic field in plasmas**
  - **ITER burning plasma: more than 10 years from now**

- **Theory: Better Understanding in Nonlinear Physics**
  - **Structure formation, zonal flow, . . .**

- **Simulation: Detailed Simulation of Individual Phenomenon**
  - **Exponential growth of computation resources and network speed**
  - **Progress in computation technique**
  - **Lack of methodology to describe a entire picture of plasmas**

Activities of BPSI

- **Meetings**

2002 Aug	Preparatory discussion	(NIFS)
2003 Aug	1st BPSI meeting	(Kyoto U)
2003 Dec	US-Japan workshop	(Kyoto U)
2004 Mar	2nd BPSI meeting	(Kyushu U)
2004 Aug	3rd BPSI meeting	(Kyushu U)
2004 Sep	US-Japan workshop	(PPPL)
2005 Apr	4th BPSI meeting during	(Kyoto U)

- **Support** from various resources
  - Grant-in-Aid from JSPS (M. Yagi, Kyushu U)
  - Part of Grant-in-Aid from MEXT (S.-I. Itoh, Kyushu U)
  - Research collaboration of RIAM, Kyushu U (M. Yagi, Kyushu U)
  - Research collaboration of NIFS (Y. Nakamura Kyoto U)
  - Research collaboration of JAERI (A. Fukuyama, Kyoto U)
  - US-Japan JIFT Workshop from JSPS (A. Fukuyama, Kyoto U)

- **Only for meeting support at present**

An Example of Standard Dataset

- **Machine ID, Shot ID, Model ID**
- **Equilibrium Data**: e.g. EFIT
- **Plasma Status Data**
  - **Plasma Fluid Data**: Fluid quantities, n_s,$\boldsymbol{u}_s$,T_s,$\boldsymbol{q}_s$
  - **Plasma Kinetic Data**: Momentum distribution, $f_s(\boldsymbol{r}, \boldsymbol{p}, t)$
  - **Electromagnetic Data**: Quasi-static $\boldsymbol{B}$, $\boldsymbol{j}$, $\boldsymbol{E}$
- **Wave Data**
  - **Wave Characteristics**: ω, $\boldsymbol{k}$, Power
  - **Electromagnetic Wave Data**: $\boldsymbol{E}$, $\boldsymbol{B}$, Ray characteristics
- **Transport Data**
  - **Particle Source and Sink**: S
  - **Momentum Source and Sink**: $j_{\rm CD}$, M_ϕ
  - **Power Source and Sink**: $P_{\rm OH}$, $P_{\rm abs}$, $P_{\rm rad}$
  - **Transport Coefficients**: D, χ

Transport Analysis

- **Level of Analysis**:
  - **TASK/TR**: **Diffusive transport equation:**
    - — **Flux-Gradient relation**
    - — **Conventional transport analysis**
  - **TASK/TX**: **Dynamical transport equation:**
    - — **Flux-averaged fluid equation**
    - — **Plasma rotation and transient phenomena**
  - **TASK/FP**: **Kinetic transport equation:**
    - — **Bounce-averaged Fokker-Plank equation**
    - — **Modification of momentum distribution**