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Integrated Modeling Activities in Japan

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in collaboration with

BPSI Working Group

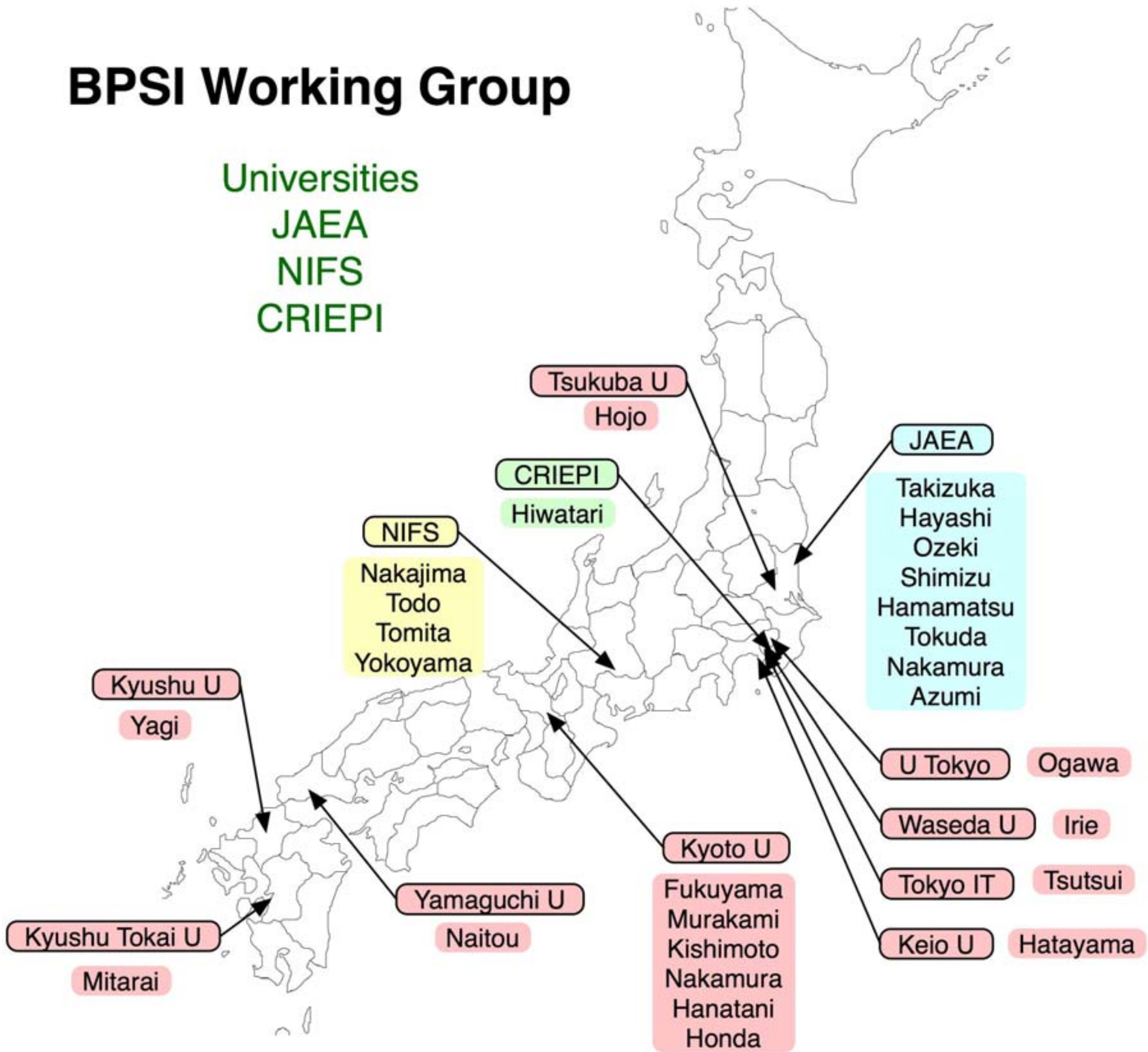
Outline

1. **BPSI** Burning Plasma Simulation Initiative
2. **TASK** Core Code for Integrated Modeling (Kyoto U)
3. **TASK/3D** Extended version of TASK for 3D (NIFS et al.)
4. **TOPICS** Integrated Modeling Code (JAEA)
5. **Summary**

BPSI: Burning Plasma Simulation Initiative

Research Collaboration of 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

Plan of BPSI

- **1st Stage**: **current status**
  - **Development of standard dataset and module interface**
  - **Integrated simulation of multi-scale 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**

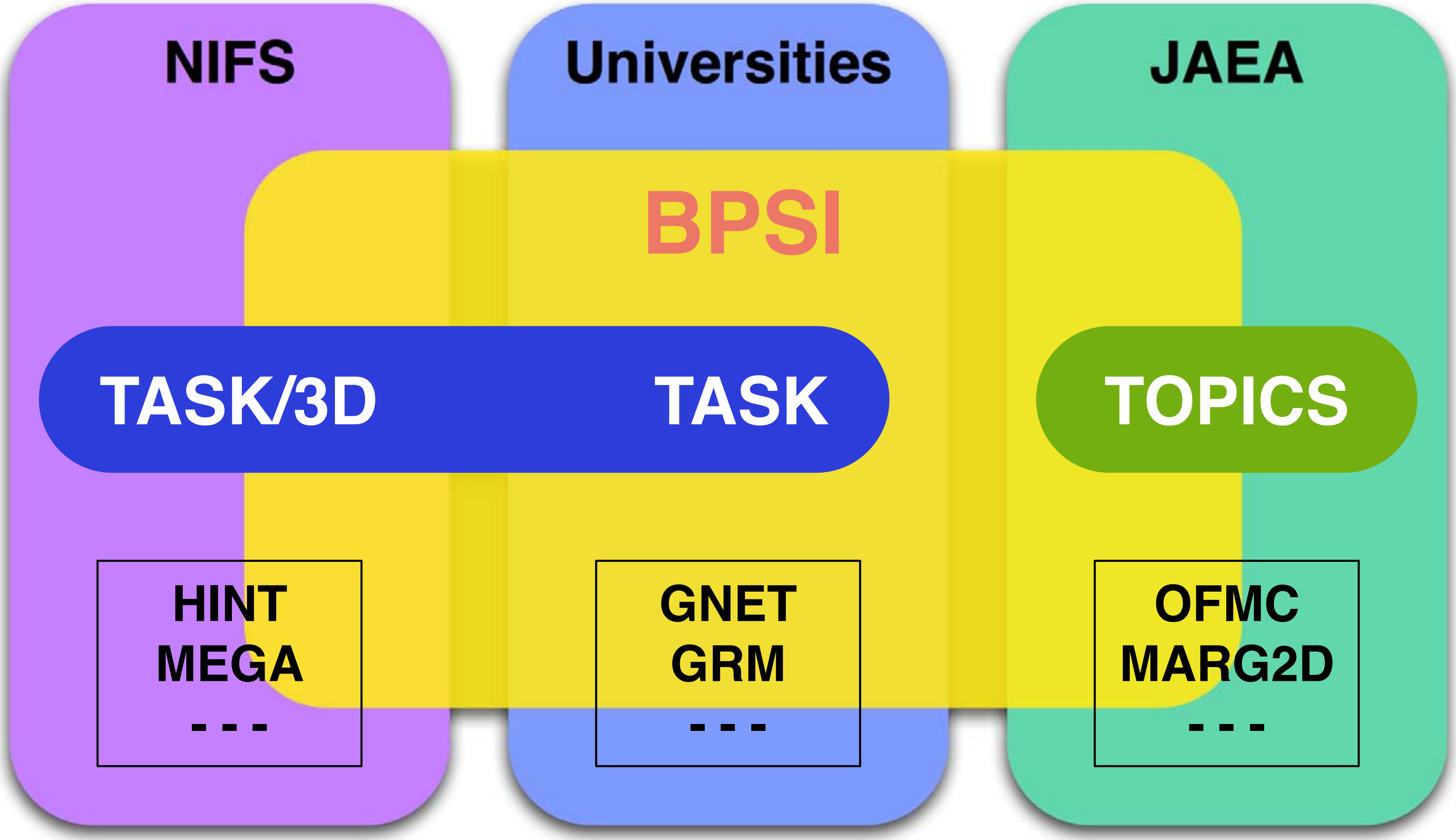
Activities of BPSI

- **Code Development**
  - **BPSI Framework**: standard dataset and interface
    - — **TASK code**: (Kyoto U)
    - — **TASK/3D for helical plasmas**: (NIFS, Kyoto U)
    - — **Predictive TOPICS for burning plasmas**: (JAEA)
  - **Development of integrated modeling**:
    - — Transport-Turbulence-MHD (Kyushu U)
    - — Core-SOL-Divertor (JAEA, CRIEPI, Tokyo U, Kyushu U)

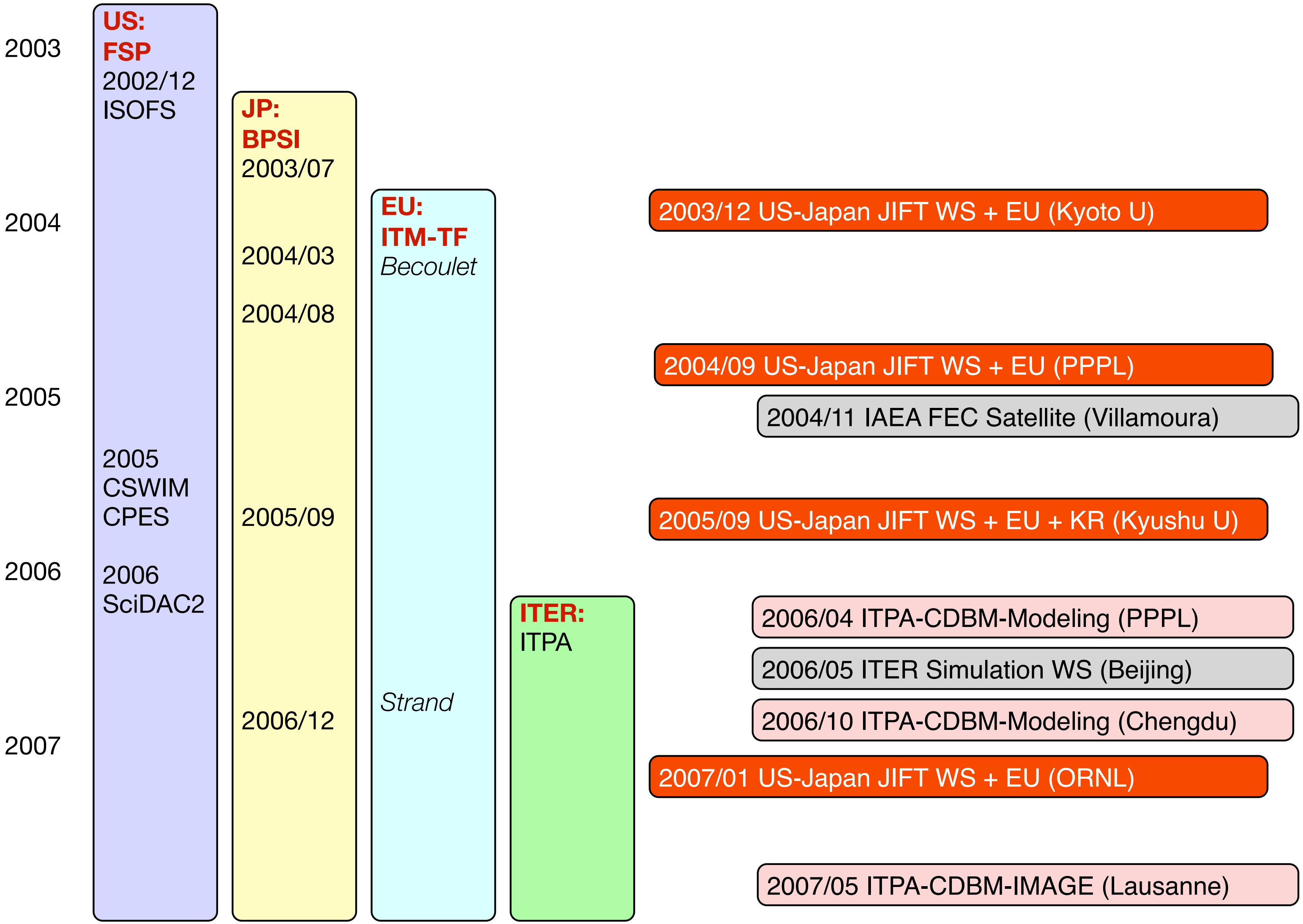
- **Support of Meetings**
  - Domestic workshops (supported by RIAM, NIFS, JAEA)
  - Workshop with experimentalists (supported by NF Forum)
  - US-Japan workshop with participation from EU
  - Korea-Japan workshop

Integrated Code Development Based on BPSI Framework

Integrated code: TASK, TOPICS and TASK/3D



International Integrated Modeling Activities



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, MPI, MDS)
    - Original graphic libraries (X11, Postscript, OpenGL)
  - **Development using CVS**
  - **Open Source**: http://bpsi.nucleng.kyoto-u.ac.jp/task/)
  - **Parallel Processing using MPI Library**

Modules of TASK

EQ	**2D Equilibrium**	Fixed/Free 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, Eigenmode
FP	**3D Fokker-Planck**	Relativistic, Bounce-averaged
DP	**Wave Dispersion**	Local dielectric tensor, Arbitrary $f(\boldsymbol{v})$
PL	**Data Interface**	Data conversion, Profile database
LIB	**Libraries**	LIB, MTX, MPI

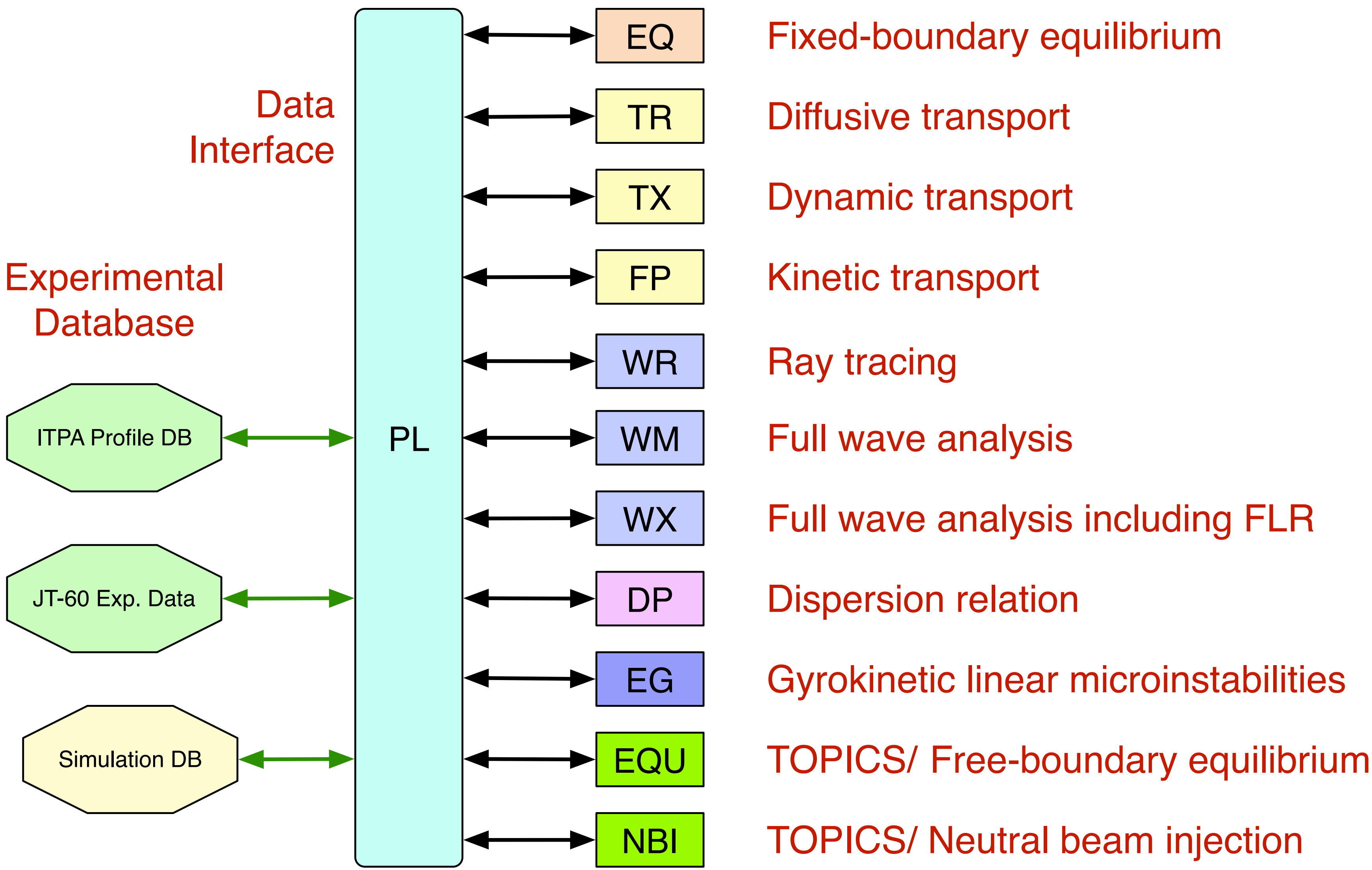
Under Development

TX	Transport analysis including plasma rotation and E_r
EG	Gyrokinetic linear stability analysis

Imported from TOPICS

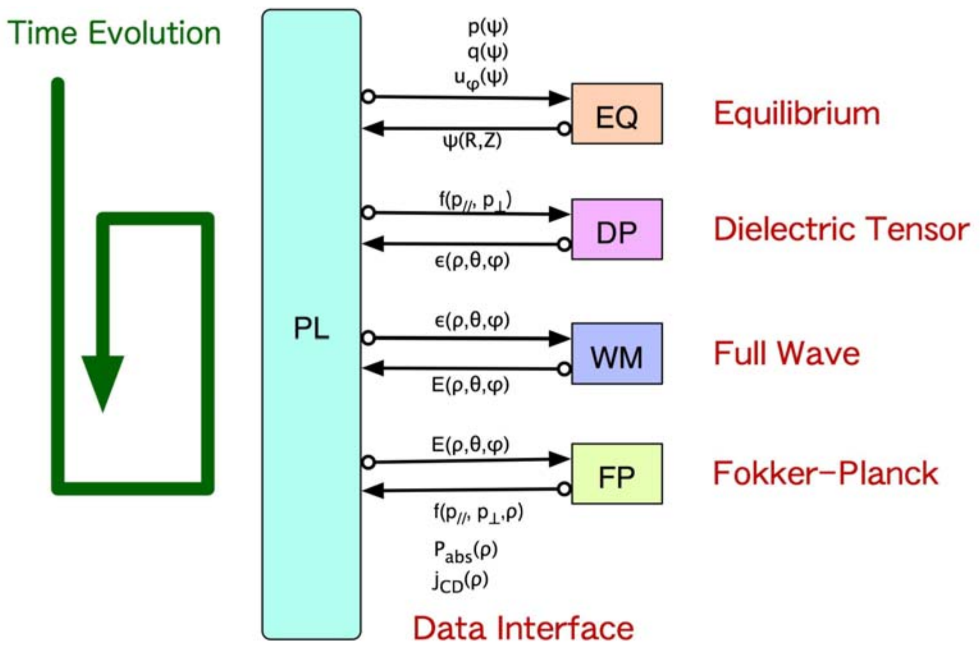
EQU	Free boundary equilibrium
NBI	NBI heating

Modular Structure of TASK



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

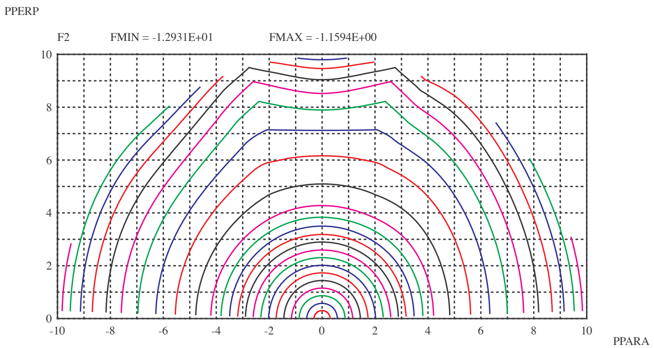
- **Modification of velocity distribution from Maxwellian**
  - Absorption of ICRF waves in the presence of energetic ions
  - Current drive efficiency of LHCD
  - NTM controllability of ECCD (absorption width)
- **Self-consistent wave analysis including modification of $f(v)$**



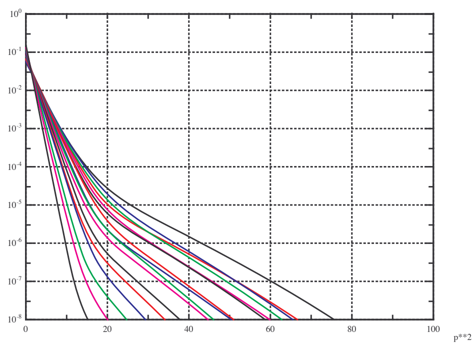
Development of Self-Consistent Wave Analysis

- **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**

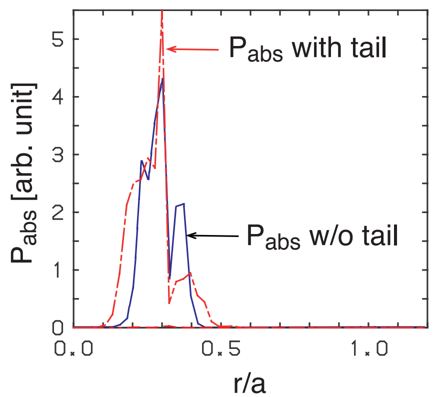
Momentum Distribution



Tail Formation



Power deposition

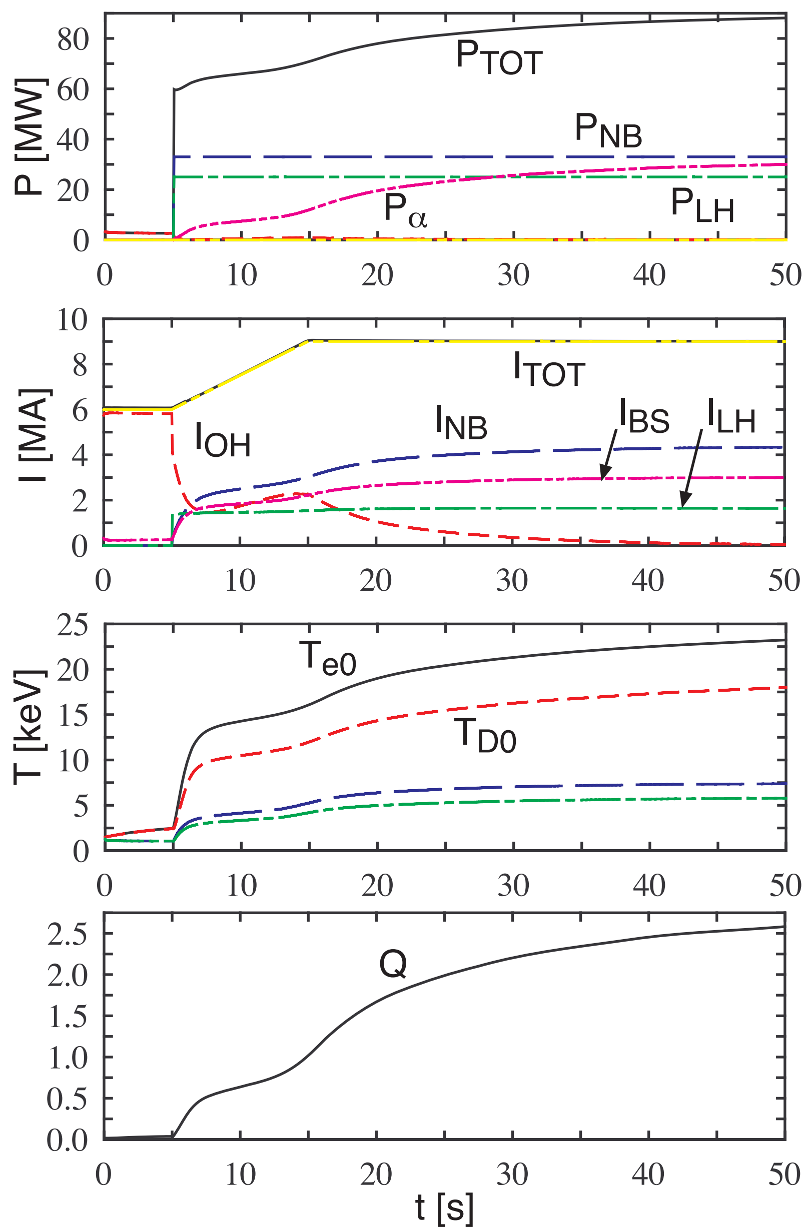


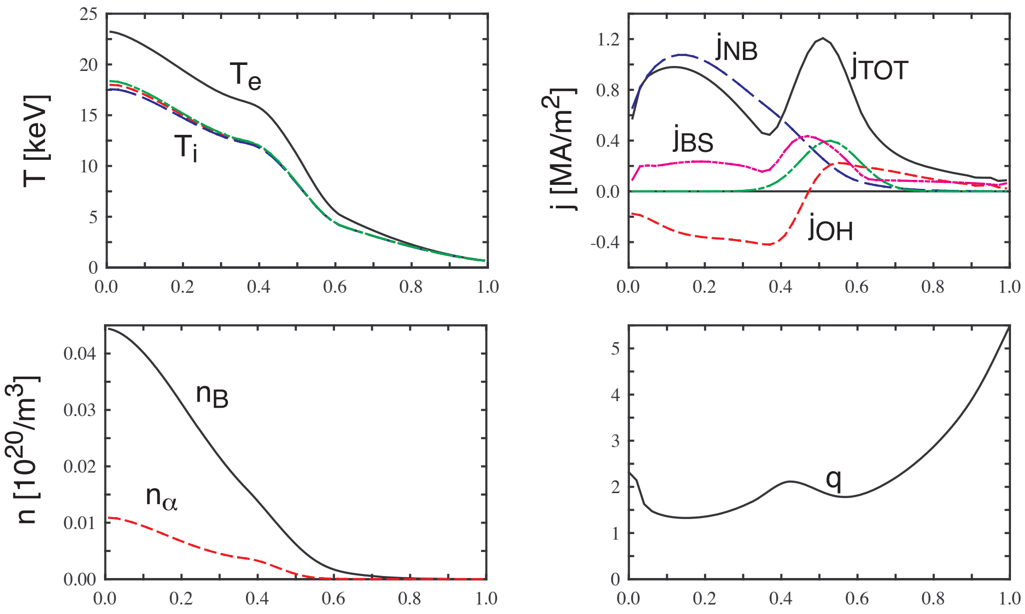
Integrated Analysis of AE in ITER Plasma

- **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: $I_\mathrm{p} = 15\,\mathrm{MA}$, $Q \sim 10$
  - Hybrid operation: $I_\mathrm{p} = 12\,\mathrm{MA}$, flat q profile above 1
  - Steady-state operation: $I_\mathrm{p} = 9\,\mathrm{MA}$, reversed shear

Steady-State Operation

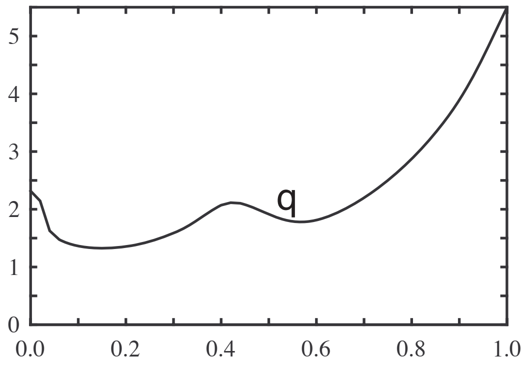
- $I_p = 6 \rightarrow 9\,\text{MA}$
- $P_{NB} = 33\,\text{MW}$
- $P_{LH} = 20\,\text{MW}$
- $Q = 10.4$
- $\beta_N = 1.8$



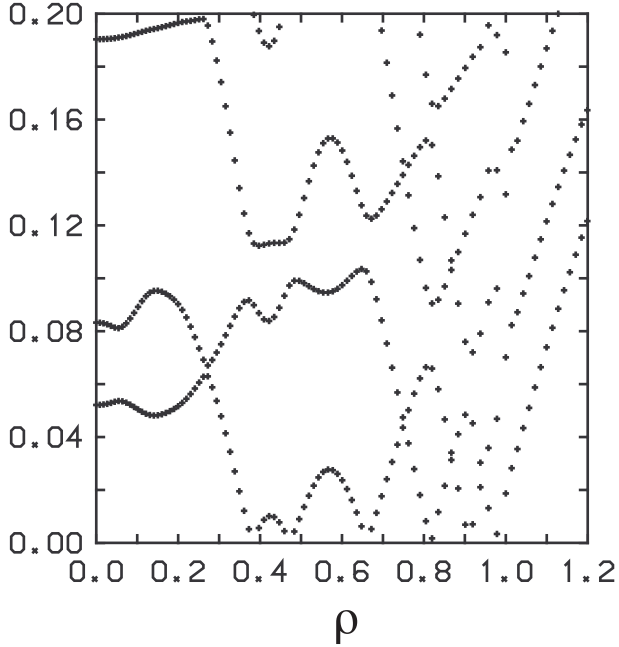


AE in Steady-State Operation

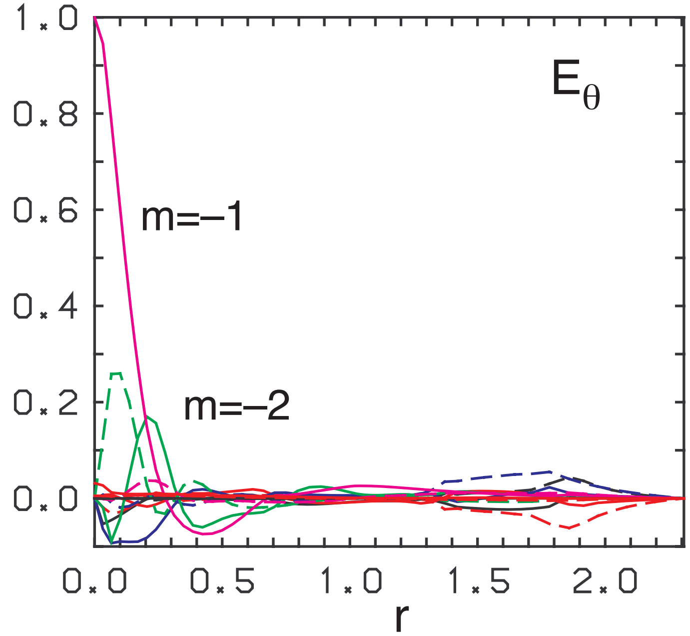
q profile



Alfvén Continuum



Mode structure ($n = 1$)



$$f_r = 109.10\,\text{kHz}$$
$$f_i = 0.77\,\text{kHz}$$

Unstable core localized mode

Preliminary

Future Plan of the TASK code

	Present Status	In 2 years	In 5 years
Equlibrium	Fixed/Free Boundary	Equilibrium Evolution	Start Up Analysis
Core Transport	1D Diffusive TR	Kinetic TR	2D Fluid TR
	1D Dynamic TR		
SOL Transport		2D Fluid TR	Plasma-Wall Interaction
Neutral Tranport	1D Diffusive TR	Orbit Following	
Energetic Ions	Kinetic Evolution	Orbit Following	
Wave Beam	Ray/Beam Tracing	Beam Propagation	
Full Wave	Kinetic ϵ	Gyro Integral ϵ	Orbit Integral ϵ
Stabilities	Sawtooth Osc.	Tearing Mode	Systematic Stability Analysis
	ELM Model	Resistive Wall Mode	
Turbulent Transport	CDBM Model	Linear GK + ZF	Nonlinear ZK + ZF
		Diagnostic Module	
		Control Module	

Access to the TASK code

- **Required Environment**
  - **Unix-like OS** (Linux, Mac OSX, $\cdots$)
  - **X-window system**
  - **Fortran95 compiler** (g95, ifort, pgf95, xlf95, sxf90, $\cdots$)
- **Source code**
  - **Stable version (original part only)**:
    - Downloadable from our 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

Extended version: TASK/3D

- **Motivation**
  - **Integrated modeling of 3D plasma in helical devices**
    - LHD, Heliotron-J et al.
  - **Modeling of tokamak plasmas including 3D effects**
    - Effects of **toroidal field ripple**: Toroidal rotation, RWM
    - Effects of **magnetic islands**: NTM, Transport

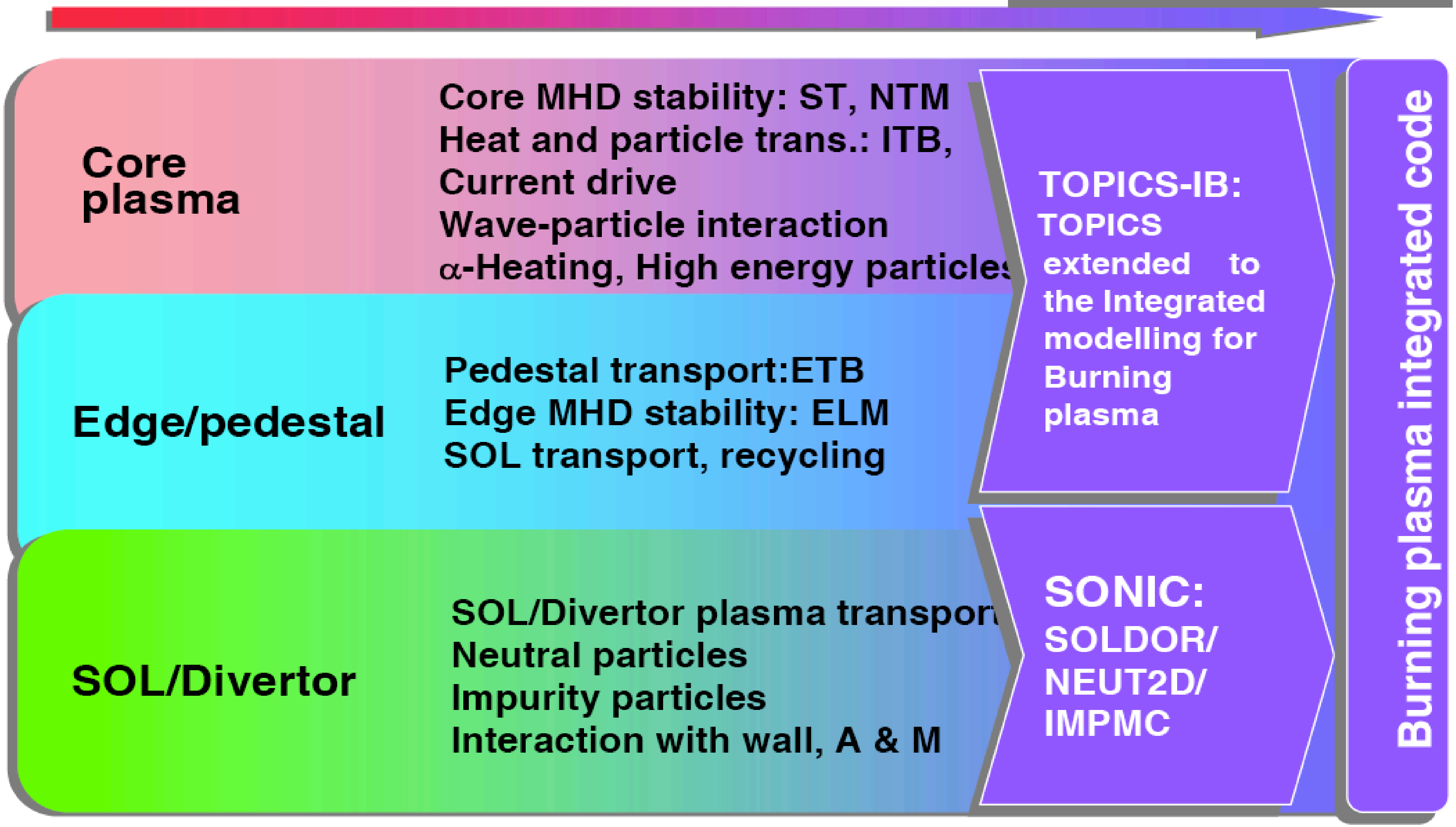
- **Extension**
  - **Interface for 3D configuration**
  - **Transport model including E_r**
  - **Modeling of magnetic island**

Modules of TASK/3D

- **3D Equilibrium**:
  - **Interface to equilibrium data from VMEC or HINT**
  - **Interface to neoclassical transport coefficient code BSC**
- **Modules 3D-ready**:
  - **WR**: Ray and beam tracing
  - **WM**: Full wave analysis
- **New module**: (**by Y. Nakamura**)
  - **EI**: Time evolution of current profile in helical geometry
- **Modules to be updated**:
  - **TR**: Diffusive transport (with an appropriate model of E_r)
  - **TX**: Dynamic transport (with neoclassical toroidal viscosity)

Development of integrated models

Integrated modelling in JAEA



TOPICS-IB: TOPICS extended to Integrated simulation for Burning plasma

Integrated modelling in JAEA

Transport code TOPICS

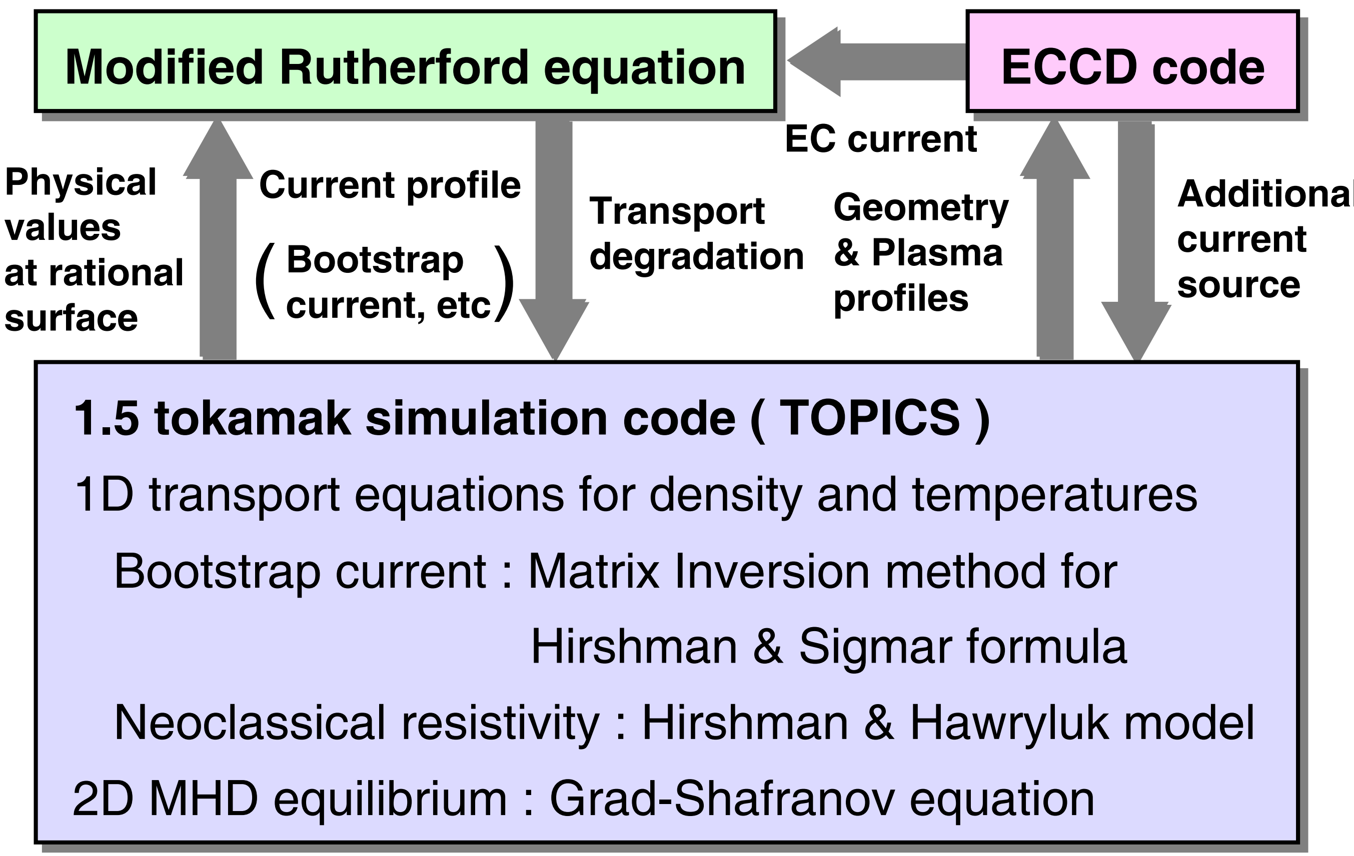
Tokamak Preduction and Interpretation Code
1D transport and 2D equilibrium, Matrix Inversion Method for NeoClassical Trans.

Transport	Transport model in core plasma
Heating, Current Drive	ECCD/ECH (Ray tracing, Relativistic F-P), NBCD(1 or 2D Fokker-Planck)
Neutral and α particles	Orbit following monte carlo, F-P, Stix
Impurity Transport	1D transport for each impurities, Radiation: IMPACT
MHD	Tearing/NTM, High-n ballooning, Low and Mid.-n MARG2D
Pedestal-SOL-Divertor	Transport in pdestal/SOL/Divertor ELM, Neutral, impurity

NTM simulation by Integrated model

Integrated modelling in JAEA

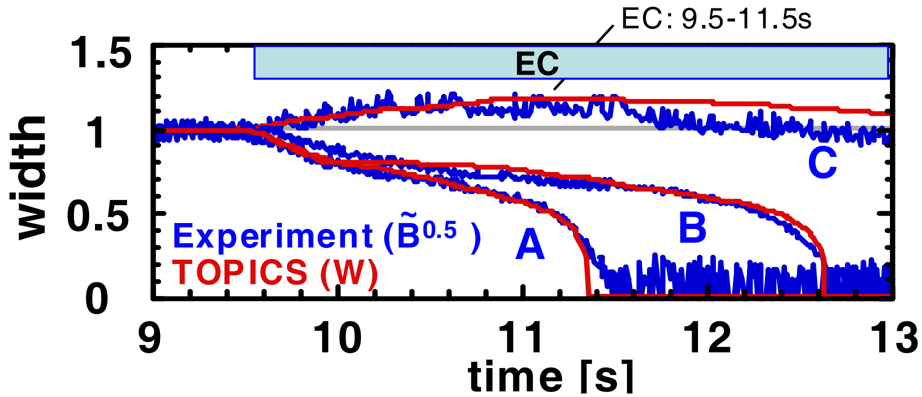
- □**Neoclassical tearing mode (NTM)** are important to access and to sustain high β and it relates to the transport and MHD.
- For the stabilization of NTM, profile control and ECCD injection were demonstrated in JT-60U.

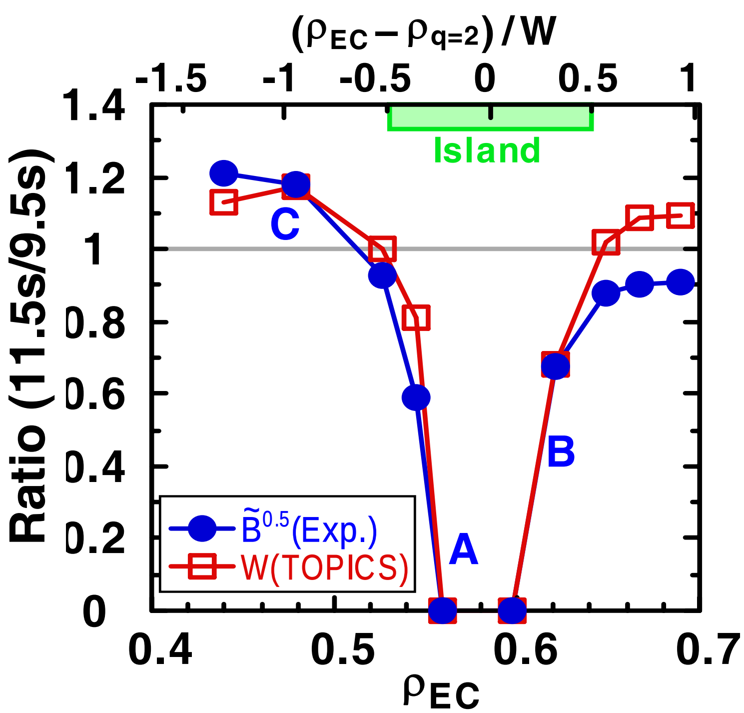


- To do the self-consistent analysis of stabilizing effect, 1.5D transport code, Modified Rutherford equation and ECCD code are integrated.

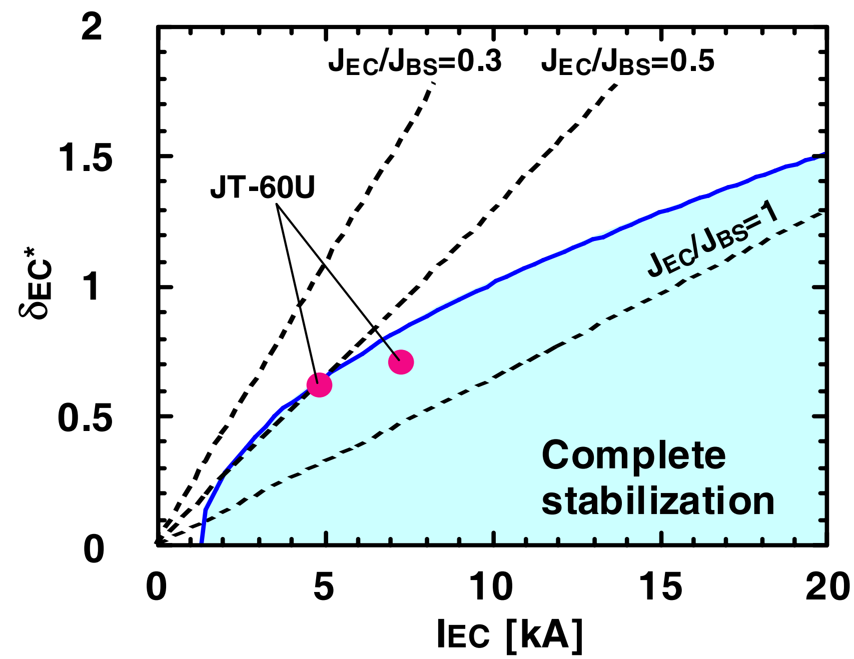
NTM simulation with modified Rutherford equation was verified by experimental results.

Integrated modelling in JAEA





- Good agreement with the same coefficient set



The consistent analysis shows:

- **ECCD width has stronger effect than amount of EC-driven current.**
- **Precise ECCD control has enabled complete stabilization with smaller value of j_{EC}/j_{BS} : J_{EC}/J_{BS} ~ 0.5**

[A. Isayama, IAEA FEC 2006]

Integrated edge-pedestal model

Integrated modelling in JAEA

1.5D core transport code (TOPICS)

1D transport & current diffusion equations

2D Grad-Shafranov equation

[N. Hayashi, IAEA FEC 2006]

2D MHD equilibrium

ELM model : Enhance transport

Heat & particle flows across separatrix

Boundary conditions at separatrix

Eigenvalue & Eigenfunction

Linear 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

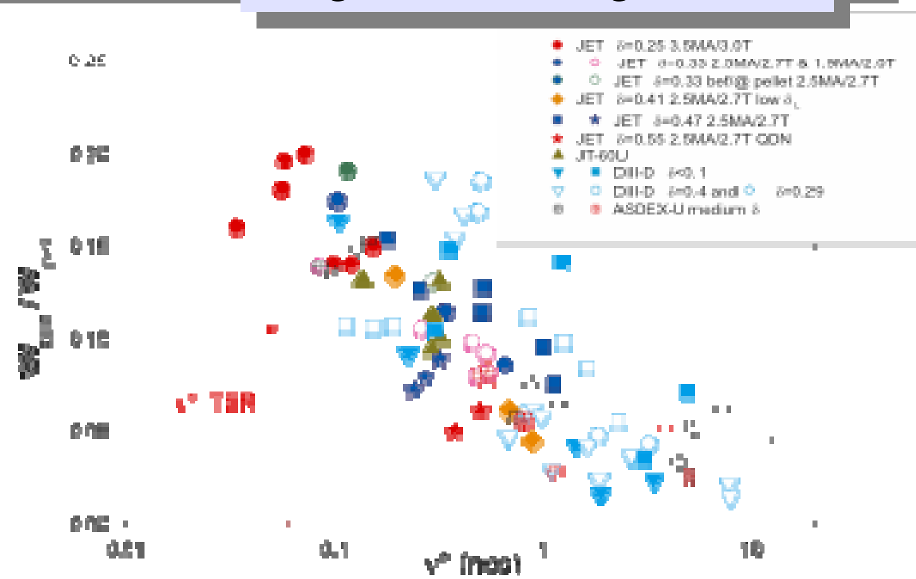
Integral fluid equations

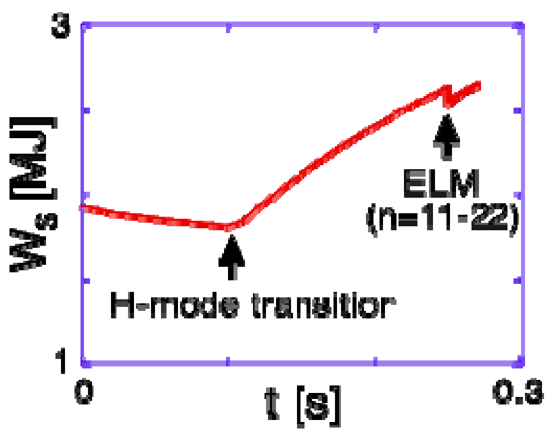
Exponential radial profiles with characteristic scale length

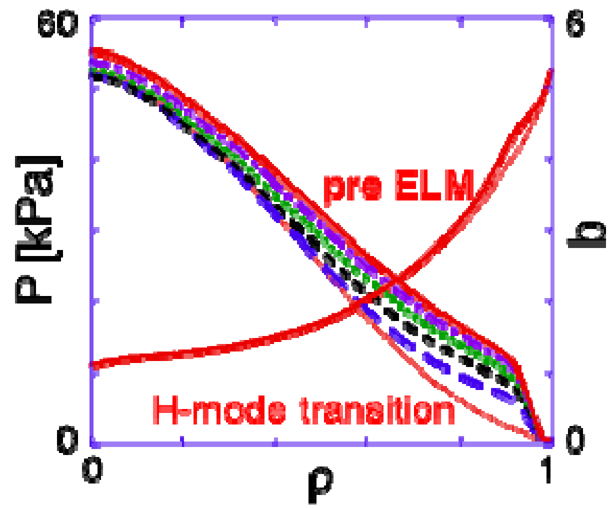
ELM energy loss simulation

Integrated modelling in JT-60U

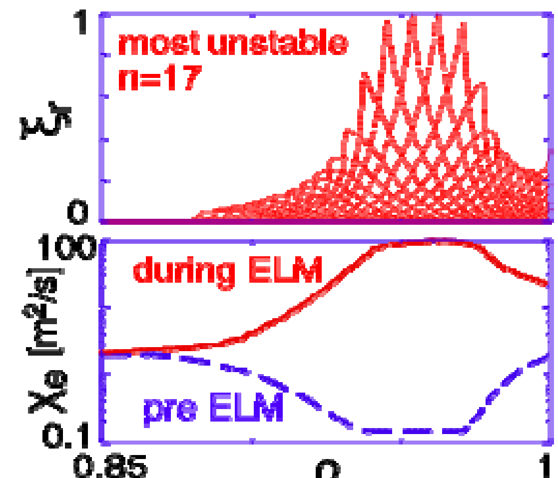
- Energy loss by ELMs is crucial for reducing the divertor plate lifetime and limiting the plasma confinement.
- ELM energy loss was found to decrease with increasing the collisionality in multi-machine experiments.
- **The collisionality dependence is investigated.**
- ELM phenomena is simulated in JT-60 parameters.







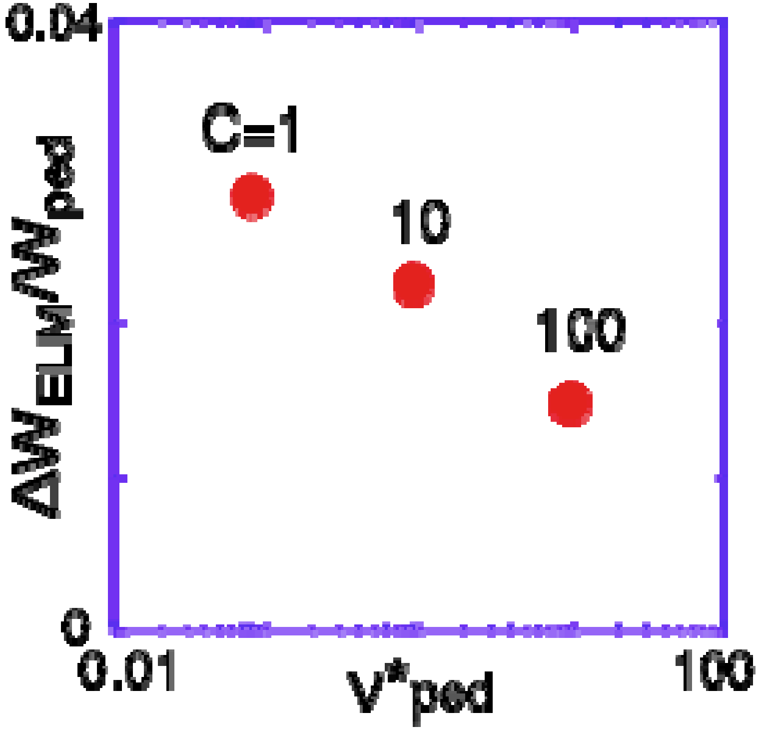
Pedestal formation : Neoclassical transport in peripheral region and anomalous in inside region.



Stabilities of n=1-30 modes are examined in each time step.

Bootstrap Current and SOL Transport through Collisionality Affects the ELM Energy Loss

Integrated modelling in JAEA



Higher ν^{*ped}

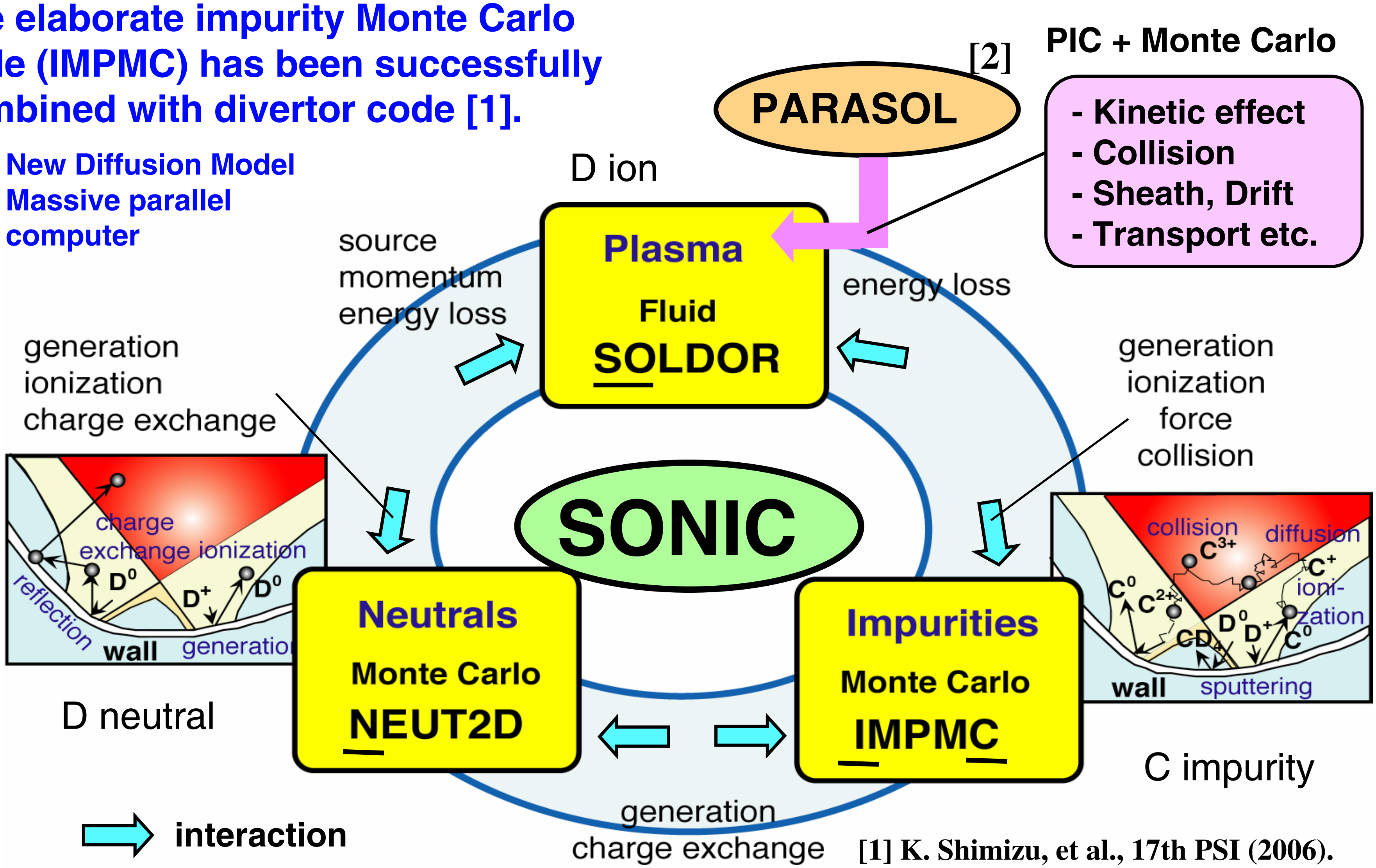
Lower J_{BS}^{ped}
Larger s^{ped}
Smaller unstable region
Smaller ΔW_{ELM}

Lower $\kappa_{//}^{SOL}$
Higher T_e^{SOL} after ELM crash
Smaller ∇T_e^{edge}
Smaller perpendicular loss
Smaller ΔW_{ELM}

Integrated SOL-divertor code:SONIC

The elaborate impurity Monte Carlo code (IMPMC) has been successfully combined with divertor code [1].

- **New Diffusion Model**
- **Massive parallel computer**



[1] K. Shimizu, et al., 17th PSI (2006).
[2] T. Takizuka, et al., 15th PSI (2002).

Summary

- Integrated modeling activity in Japan is coordinated with **Burning Plasma Simulation Initiative**.
- **Standard dataset** and **module interface** for integrated modeling have been proposed and partially implemented in TASK.
- The **TASK** code has been developed as a reference core code for BPSI and applied to the prediction of ITER plasmas.
- The development of the extended version **TASK/3D** has started aiming at not only helical plasmas but also 3D effects in tokamaks.
- Predictive **TOPICS** has been successfully combined with various codes (MHD, SOL, EC) for integrated modeling.
- Benchmark test and module exchange between **TASK** and **TOPICS** are in progress.