Fusion Simulation Activities in Japan

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Outline

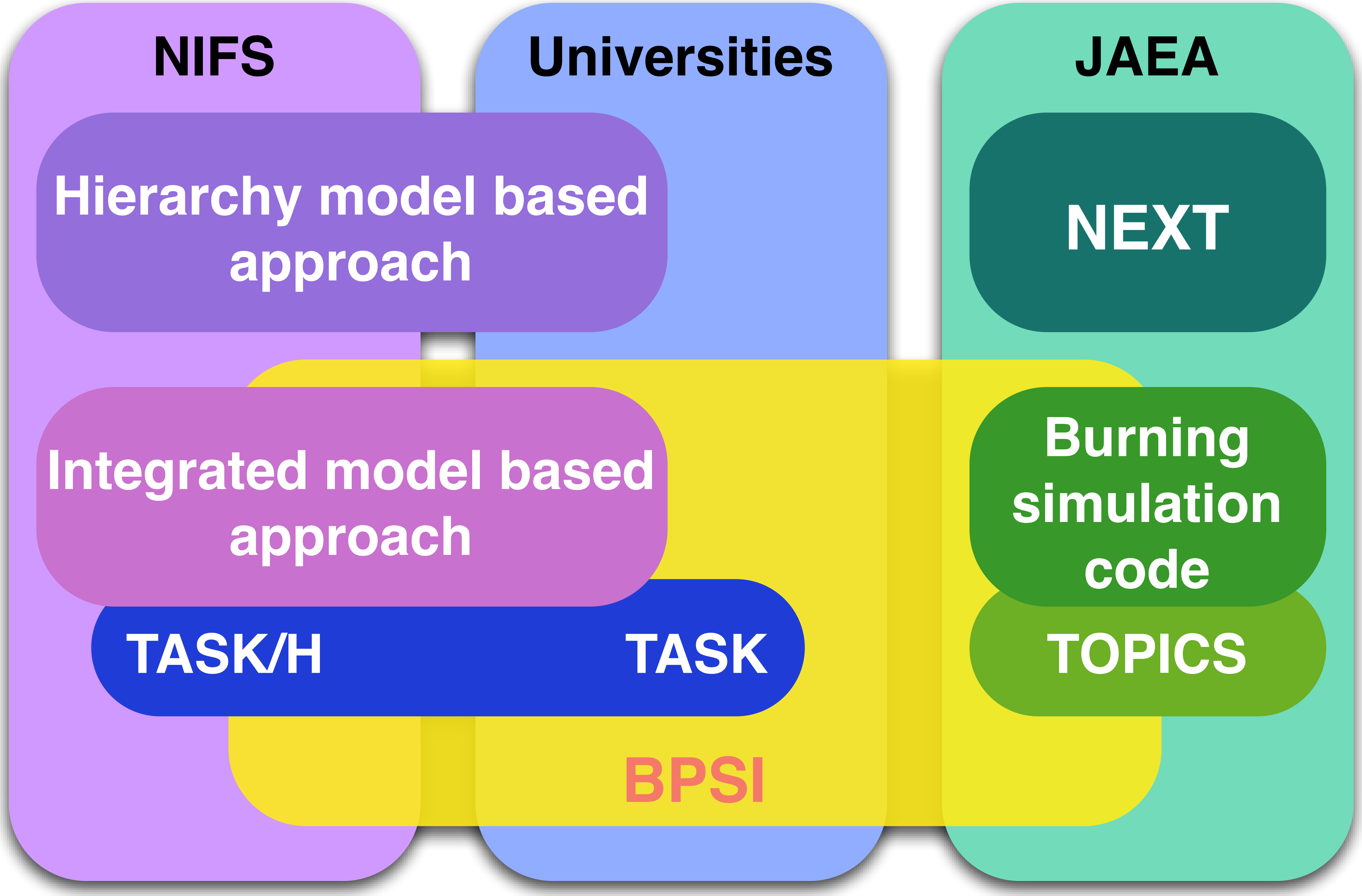
- **Overview**
- **Multi-scale simulations in NIFS**
  · · · Tomorrow morning (Nakajima)
- **NEXT: numerical experiment project in JAEA**
- **BPSI: burning plasma simulation initiative**
- **TASK: Integrated modeling code system**
  · · · Tomorrow afternoon (Fukuyama)
- **Integrated modeling activities in JAEA**
- **ITER-BA computer simulation center**

Overview

- **Computer simulation has been playing a key role in plasma physics nd nuclear fusion research in Japan**
  - **Proof of principle simulations**: complicated phenomena
  - **First principle simulations**: large-scale nonlinear phenomena
  - computer resources limited the range of time and spatial scales

- **Advances in understanding of nonlinear plasma physics and computer technology lead to new trend of fusion plasma simulations**
  - **Multi-scale physics simulations**: with wide range scales
  - **Integrated modeling**: with interacting various modules

Simulation Research in Japan



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Multi-Scale Simulations in NIFS

NIFS: National Institute for Fusin Science

Integrated model based approach

TASK/H
3D Helical Extension of
Integrated modeling code TASK

Hierarchy model based approach

MINOS: MHD simulation code
MEGA: MHD & EP hybrid code
CAP: multi-phase fluid code
GKV: gyrokinetic-Vlasov code
etc

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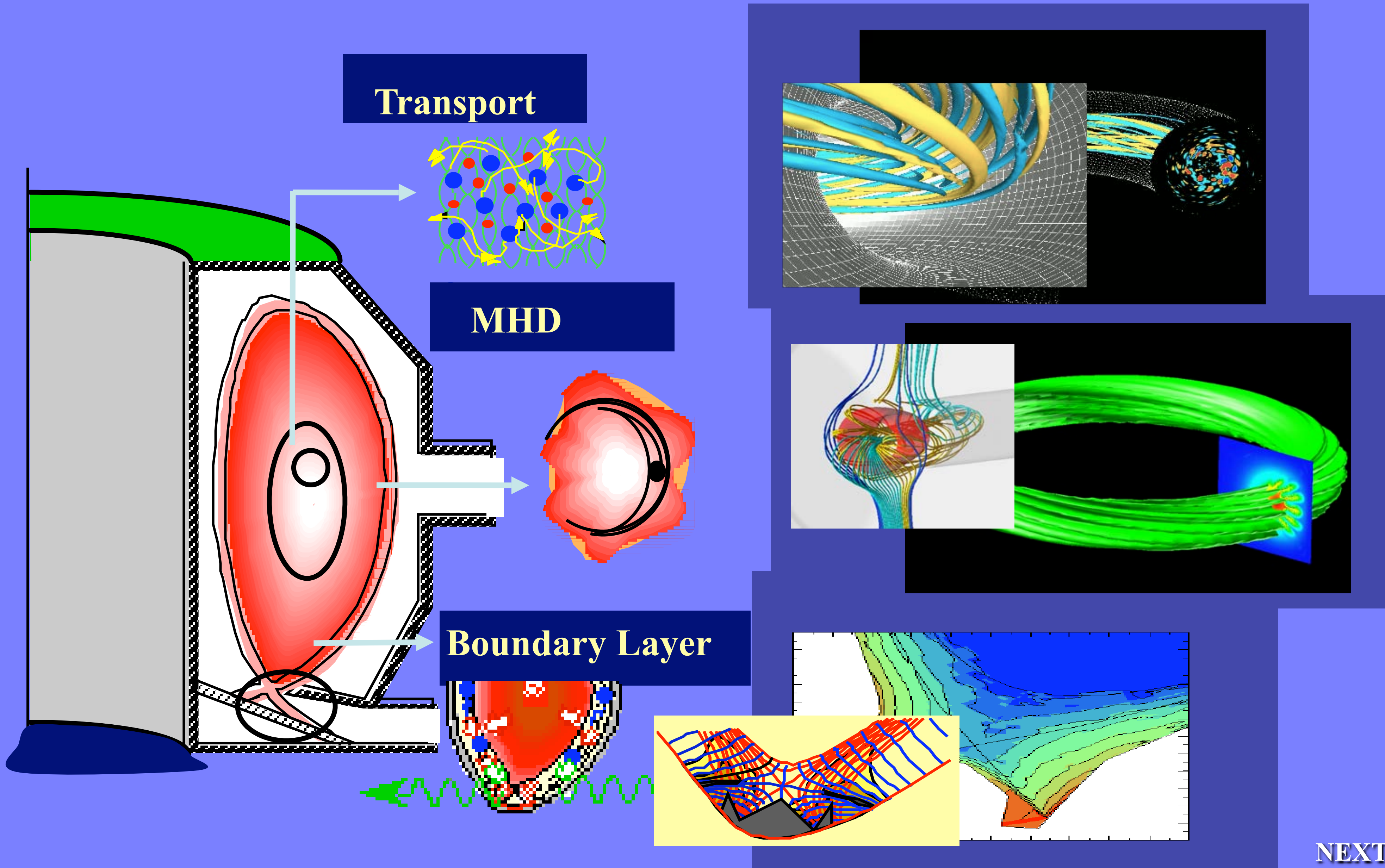
NEXT : Numerical Experiment of Tokamaks

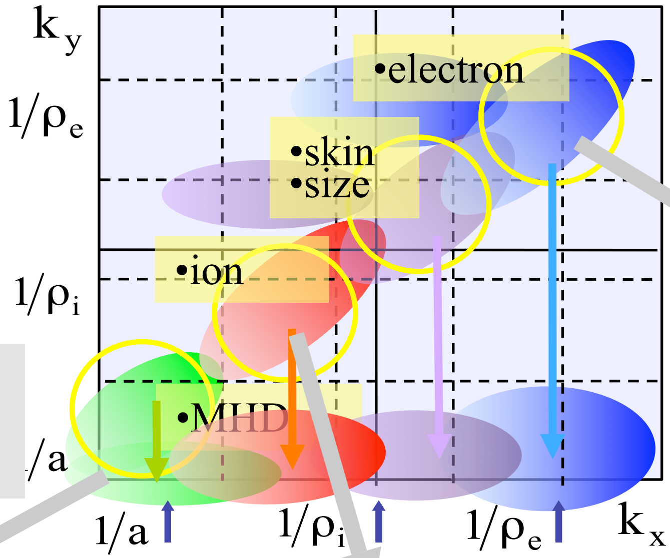
Principle based fusion research through advanced computation



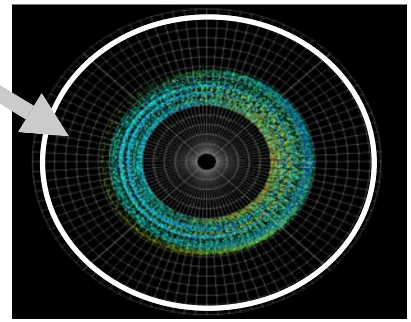
NEXT

Key code development covering plasma dynamics with wide spatio-temporal scales

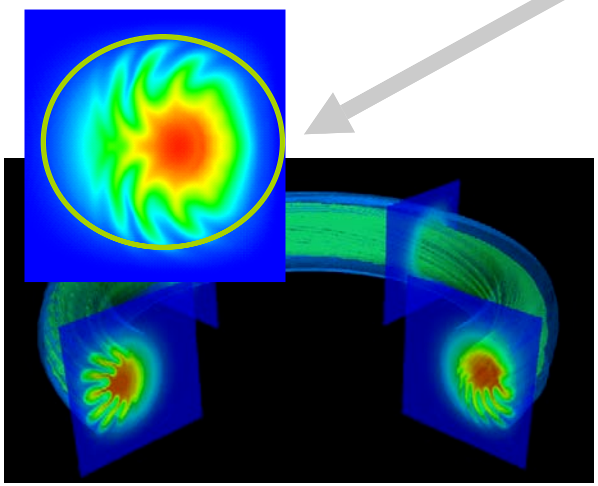
NEXT



Global Gyro-kinetic toroidal ETG code

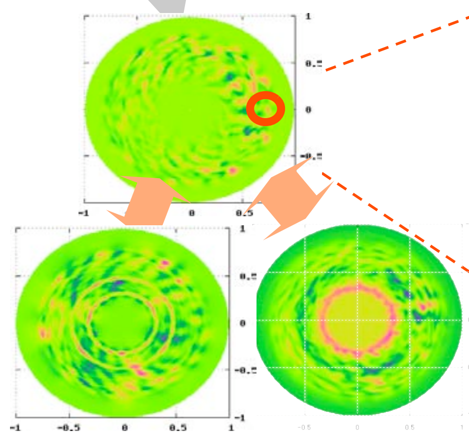


Compressible nonlinear MHD code using finite volume methd



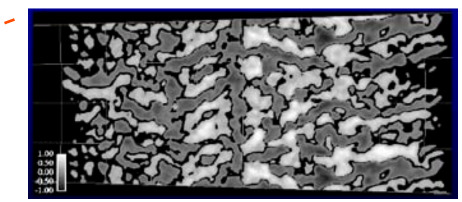
Internal kink affected by ballooning mode

T_i

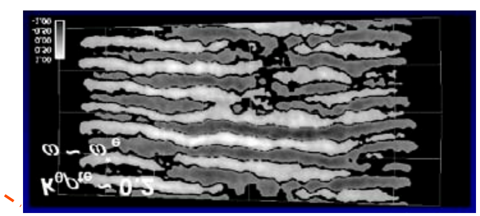


Zonal-A **Zonal-ϕ**

Electromagnetic Gyro-Fluid toroidal code



Reversed magnetic shear



Normal magnetic shear

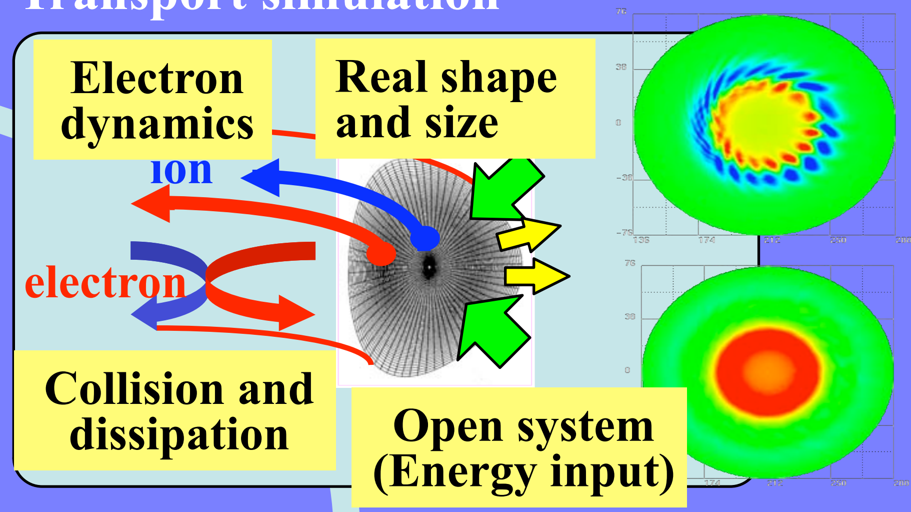
Code Development in NEXT Project

Systematic development of codes under toroidal geometry

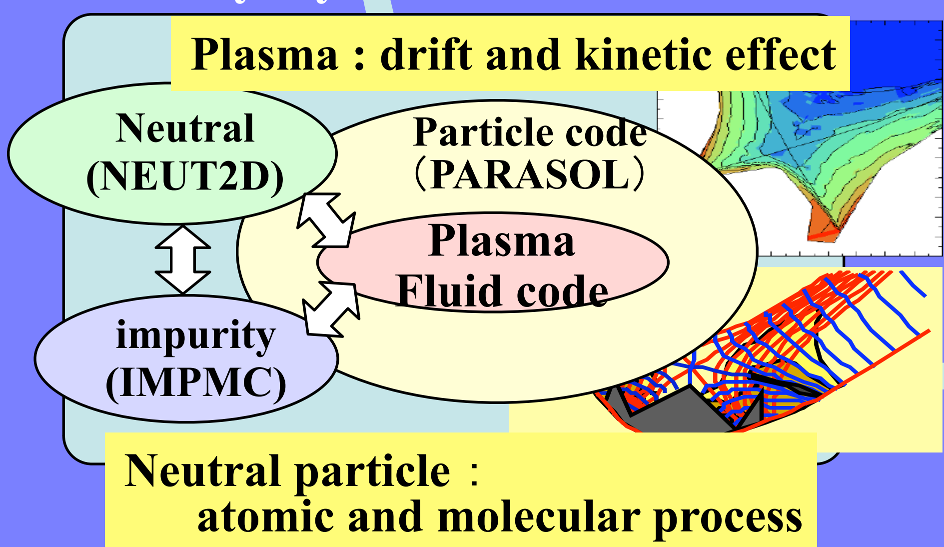
Purpose: real shape and size
Open system

- **Qualitative and quantitative prediction in each physical layer**
- **Connection among different layers**

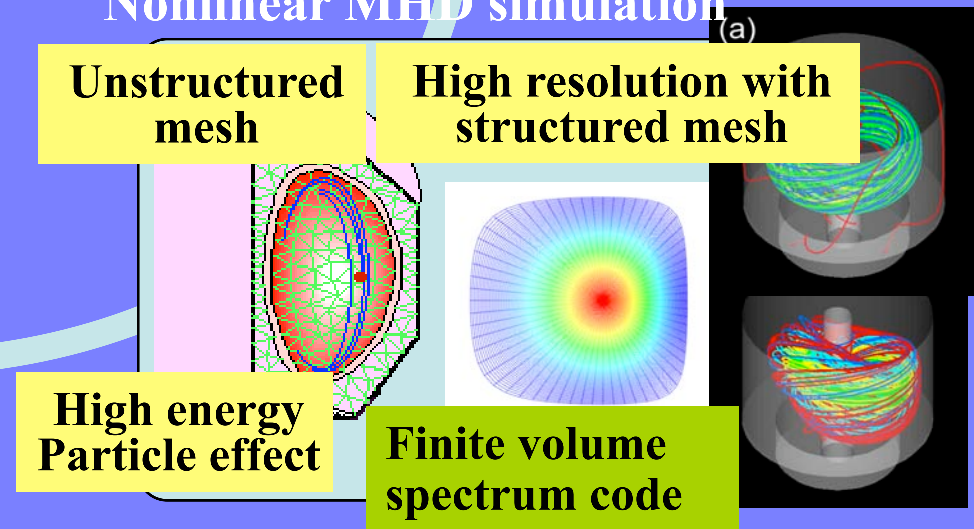
Transport simulation



Boundary layer and diverter simulation



Nonlinear MHD simulation

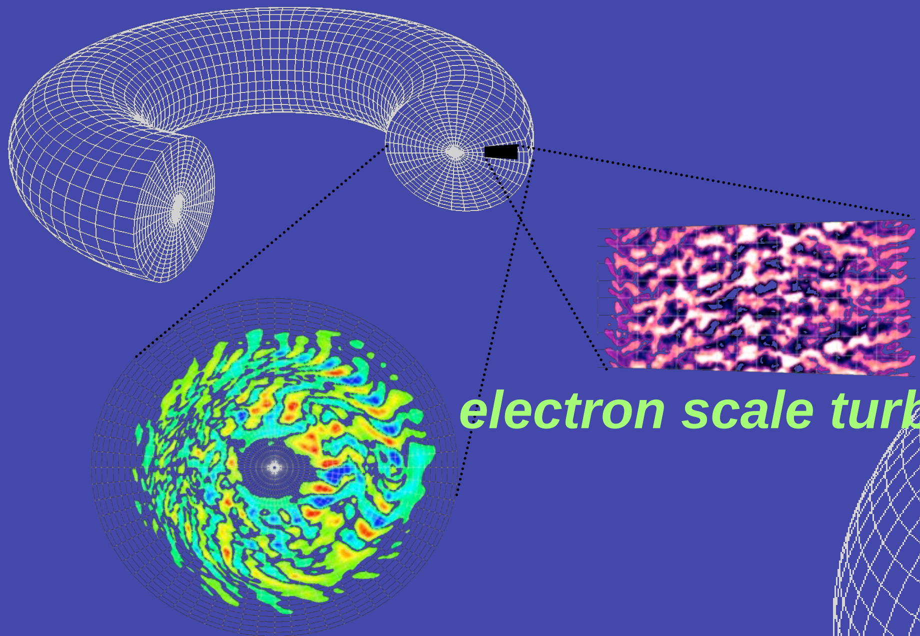


First-Principle Simulation Code Cluster (NEXT project in JAEA)

MHD	Linear Stability	MARG2D ERATO	Ideal MHD	3D toroidal
		AEOLUS	Resistive MHD	3D toroidal
	Nonlinear simulation	MHFVSP	Compressible	3D, 3D toroidal
		ALSTOR_NEO	Reduced set	3D, 3D toroidal
Core Transport	Nonlinear turbulence simulation	R5F	Landau fluid model	3D, 3D toroidal
		GFS		3D local
		G3D, GT3D ρ_i scale, ρ_e scale	Gyro kinetic model	3D, 3D toroidal
DIVERTOR	SOL-divertor simulation	SONIC (SOLDOR + NEUT2D + IMPMC)	Integrated divertor code	2D toroidal
		PARASOL	Particle model	2D (2D toroidal)

Target problem of fusion plasma simulation

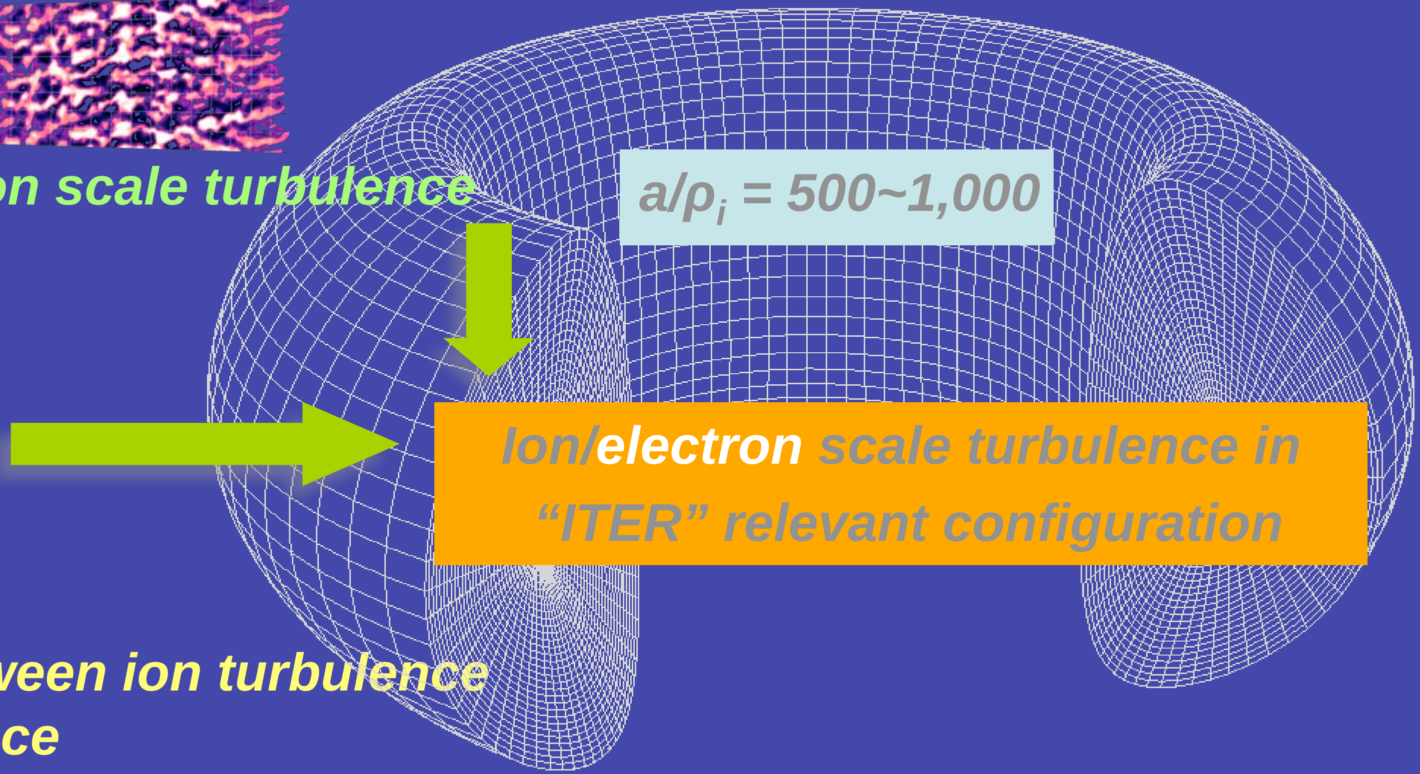
$$\frac{\text{plasma radius } a}{\text{ion gyro radius } \rho_i} \sim 150$$



ion scale turbulence

Target simulation

- *"ITER" relevant realistic configuration*
- *Overcome different scale hierarchy via computational resources*
- *Computer resource → 1~10PFlops*



Present simulation

- *Small machine size*
- *Scale separation between ion turbulence and electron turbulence*
- *Computational resource → 0.5TFlops*

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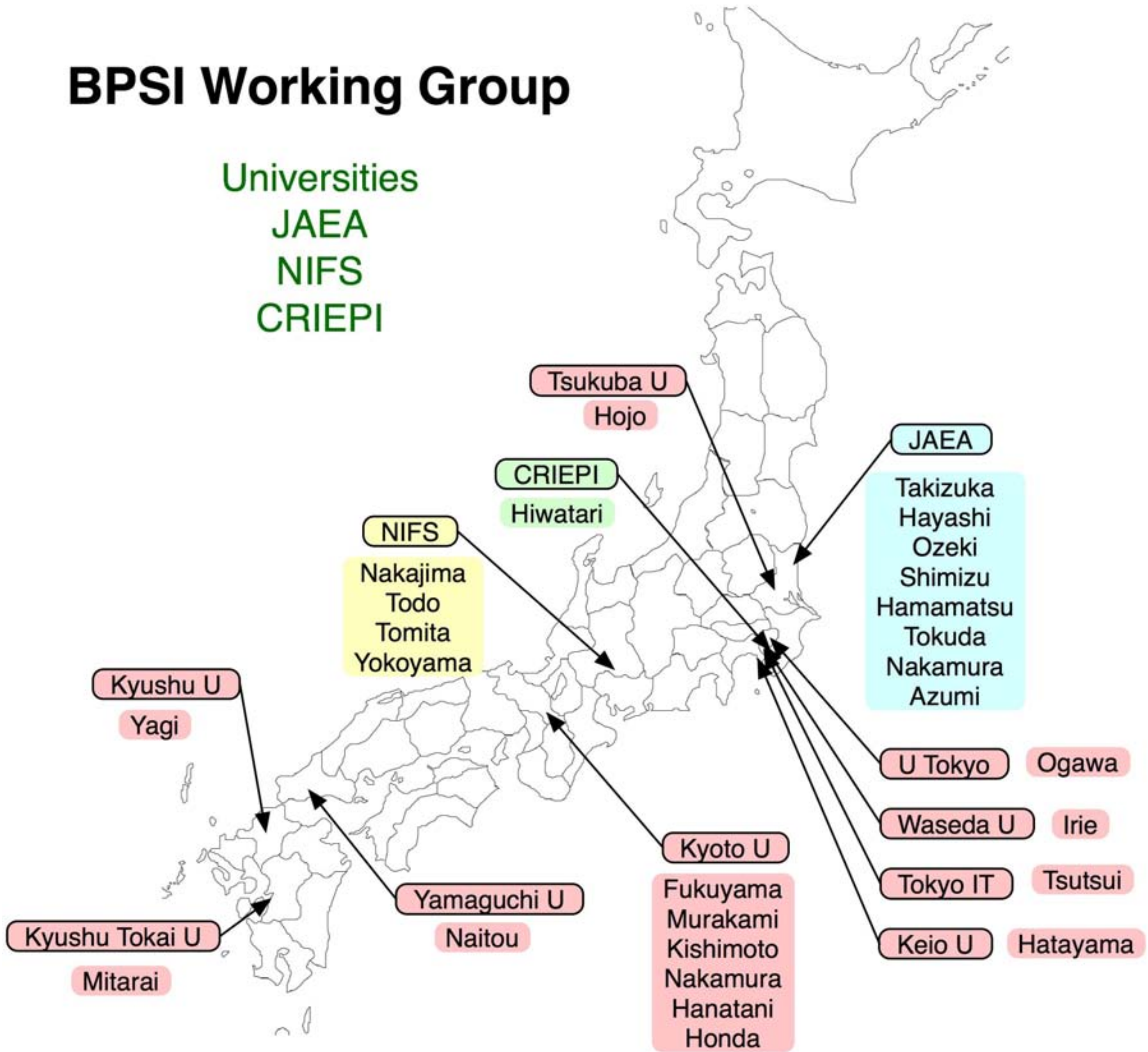
BPSI: Burning Plasma Simulation Initiative

Research Collaboration among Universities, NIFS and JAEA

Since 2002



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** (validation with experimental data)

    — **Reasonable computer resources** (still limited)

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

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

Status of BPSI

- **1st Stage**:**present 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**

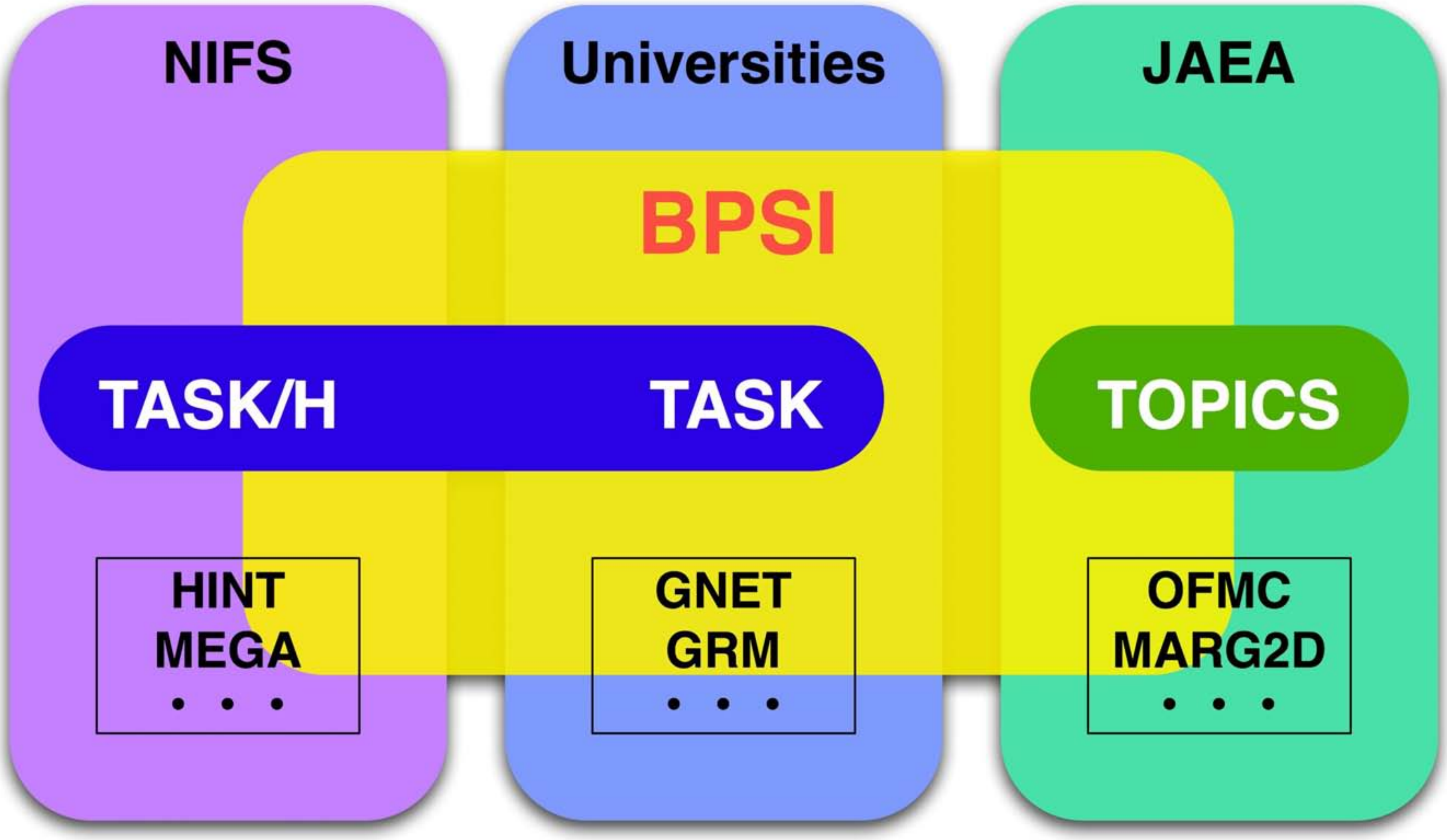
Activities of BPSI

- **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

- **Code Development**
  - **BPSI Framework**: standard dataset and interface
    - **TASK code**: (Kyoto U)
    - **TASK/H 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)

BPSI: Burning Plasma Simulation Initiative

Integrated code: TASK and TOPICS



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TASK Code

- **T**ransport **A**nalysing **S**ystem for Tokama**K**
- **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 and MPI)
    - — Own graphic libraries (X11, eps, OpenGL)
  - **Development using CVS** (Concurrent Version System)
    - — Open Source (Pre-release with f77: http://bpsi.nucleng.kyoto-u.ac.jp/task/)
  - **Parallel Processing using MPI Library**
  - **Extension to Toroidal Helical Plasmas**

Modules of TASK

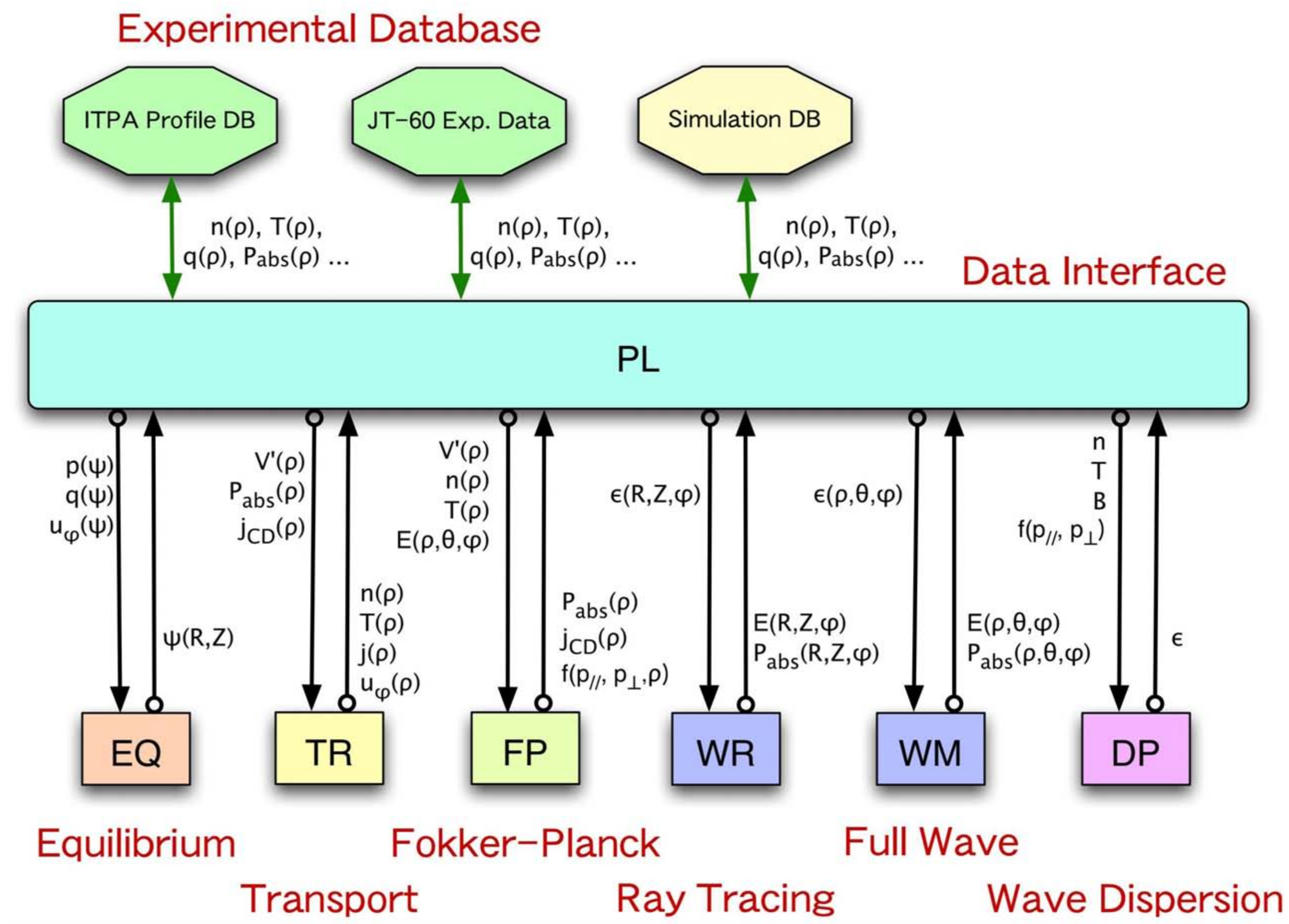
EQ	**2D Equilibrium**	Fixed/Free boundary, Toroidal rotation
TR	**1D Transport**	Diffusive transport, Transport models
WR	**3D Geometr. Optics**	EC, LH: Ray tracing, Beam tracing
WM	**3D Full Wave**	IC, AW: Antenna excitation, Eigen mode
FP	**3D Fokker-Planck**	Relativistic, Bounce-averaged
DP	**Wave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

Under Development

TX	Transport analysis including plasma rotation and E_r
WA	Global linear stability analysis
WI	Integro-differential wave analysis (FLR, $\boldsymbol{k} \cdot \nabla B \neq 0$)

All developed in Kyoto U

Modular Structure of TASK



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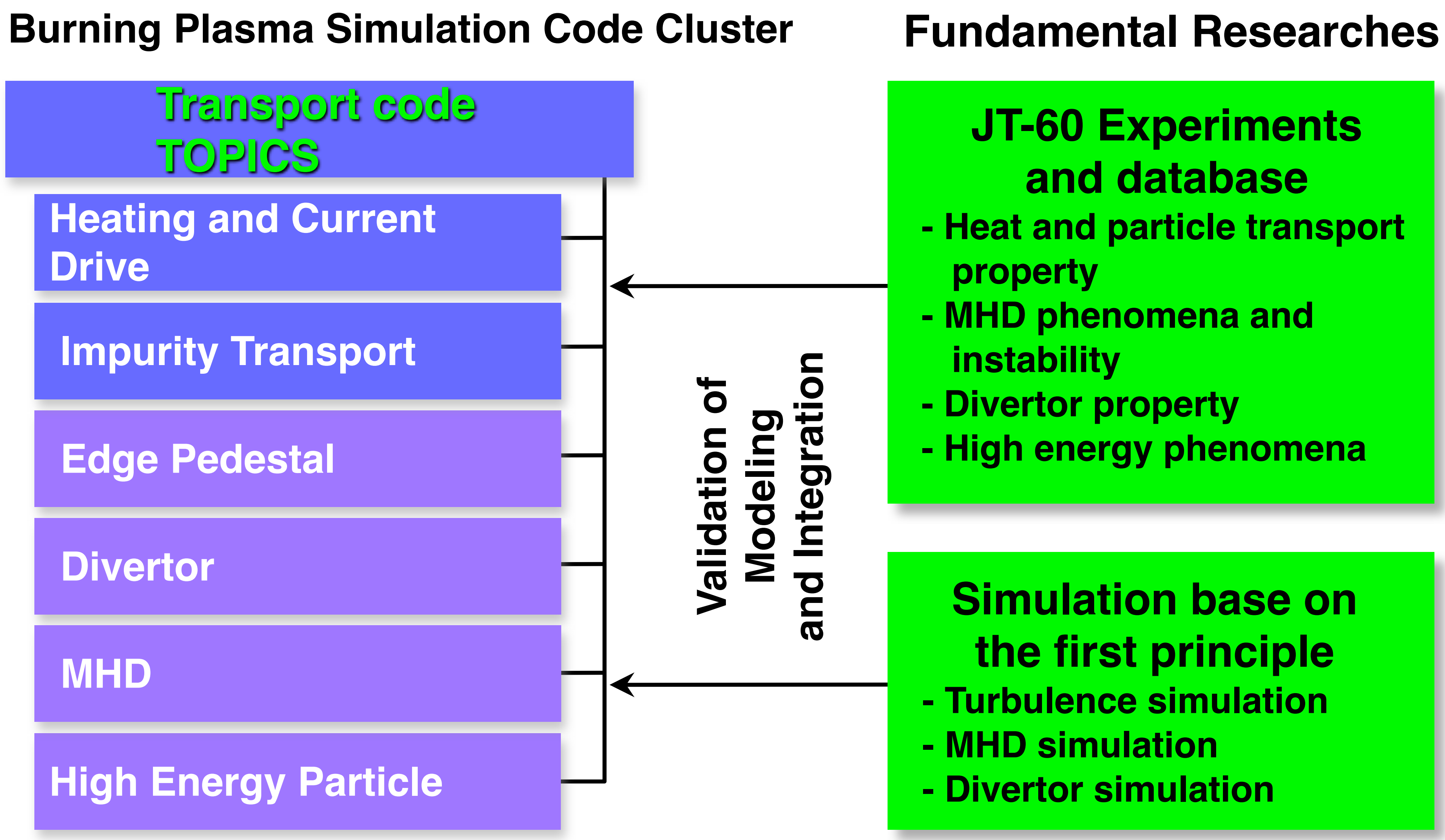
Strategy for Burning Plasma Research



Burning Plasma Simulation Code Cluster in JAEA

Transport code TOPICS

Tokamak Prediction and Interpretation Code
Time dependent/Steary state analyses
1D transport and 2D equilibrium Matrix
Inversion Method for NeoClassical Trans.

- **Heating & Current Drive** — ECCD/ECH (Ray tracing, Relativistic F-P), NBCD (1 or 2D F-P)
- **Impurity Transport** — 1D transport for each impurities,Radiation: **IMPACT**
- **Edge Pedestal**
- **Divertor** — Perp. and para. transport in SOL and Divertor, Neutral particles, Impurity transport on SOL/Div. : **SOLDOR**, **NEUT2D**, **IMPMC**
- **MHD** — Tearing/NTM, High-n ballooning, Low-n: **ERATO-J**, Low and Mid.-n **MARG2D**
- **High Energy Behaviour** — Transport by α-driven instability:**OFMC**

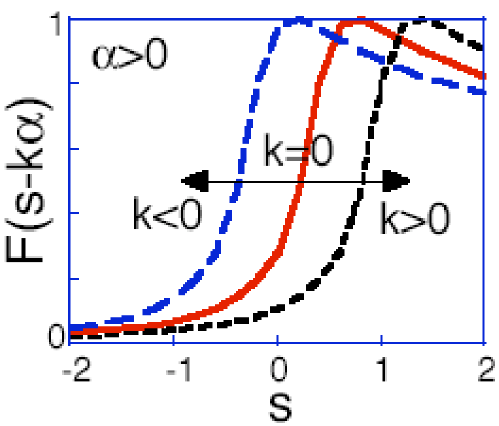
Transport Model for ITB

Sharp reduction of anomalous transport in RS region (k ~ 0) can reproduce JT-60U experiment of strong RS current-hole plasmas

(N. Hayashi et al., Nucl. Fusion 45 (2005) 933)

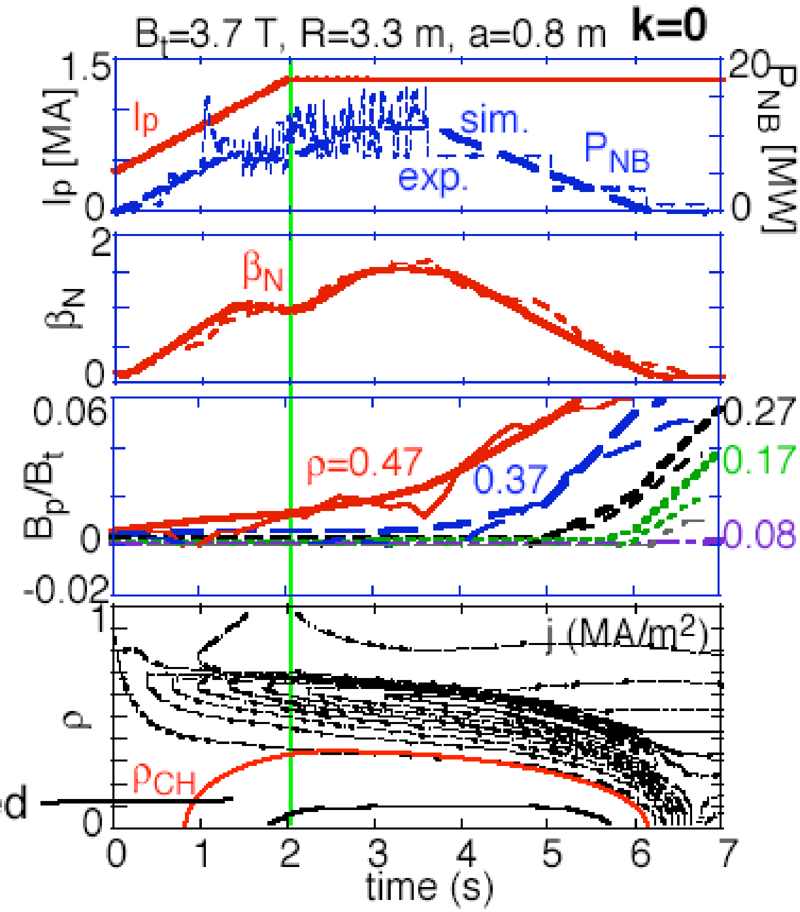
Transport becomes neo-classical level in RS region, which results in the autonomous formation of ITB and strong RS through large bootstrap current.

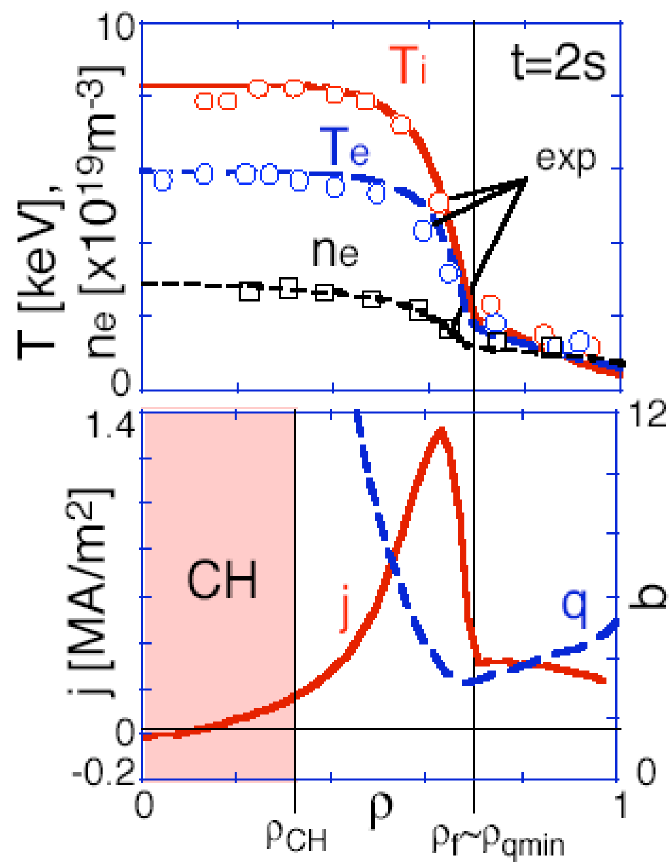
$$\chi_{ano} = \chi_0 F(s - k\alpha)$$



(F with k=1 : CDBM)

Inside CH region :
Current limit model based on ATMI equilibrium



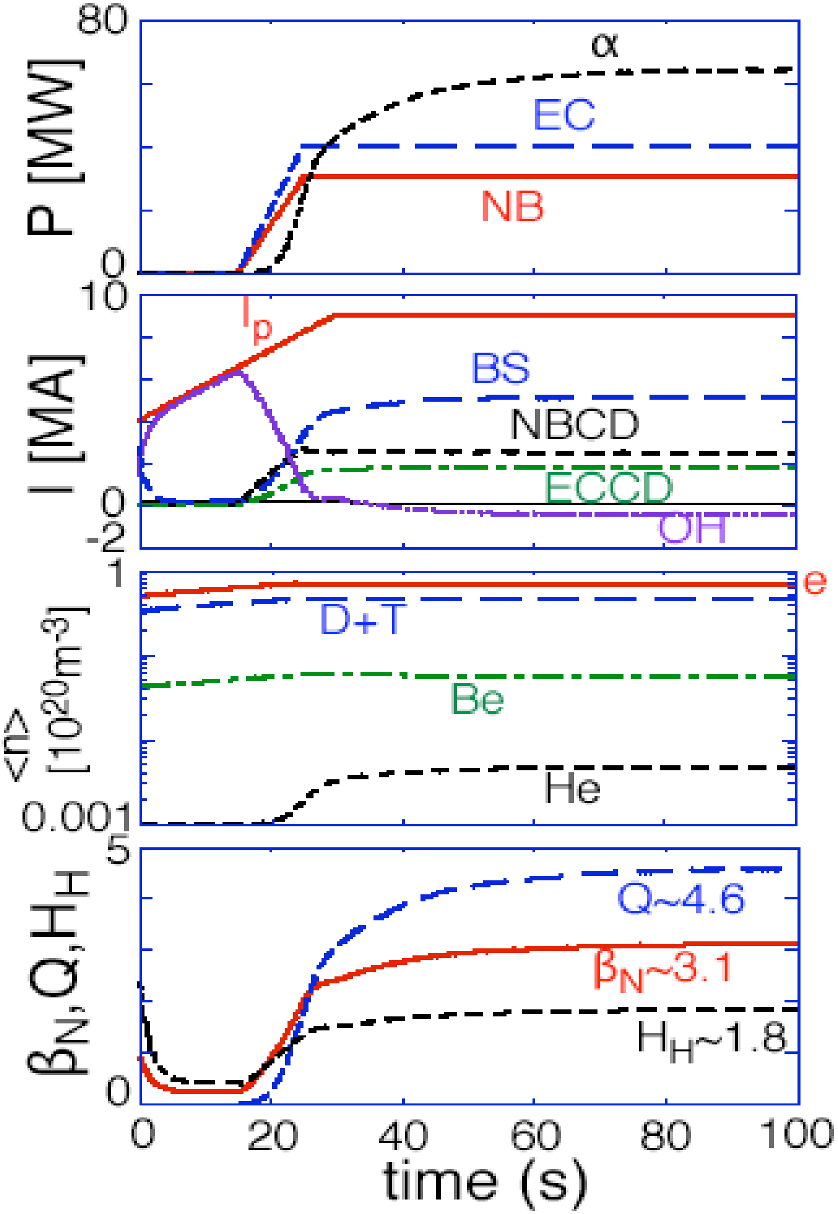


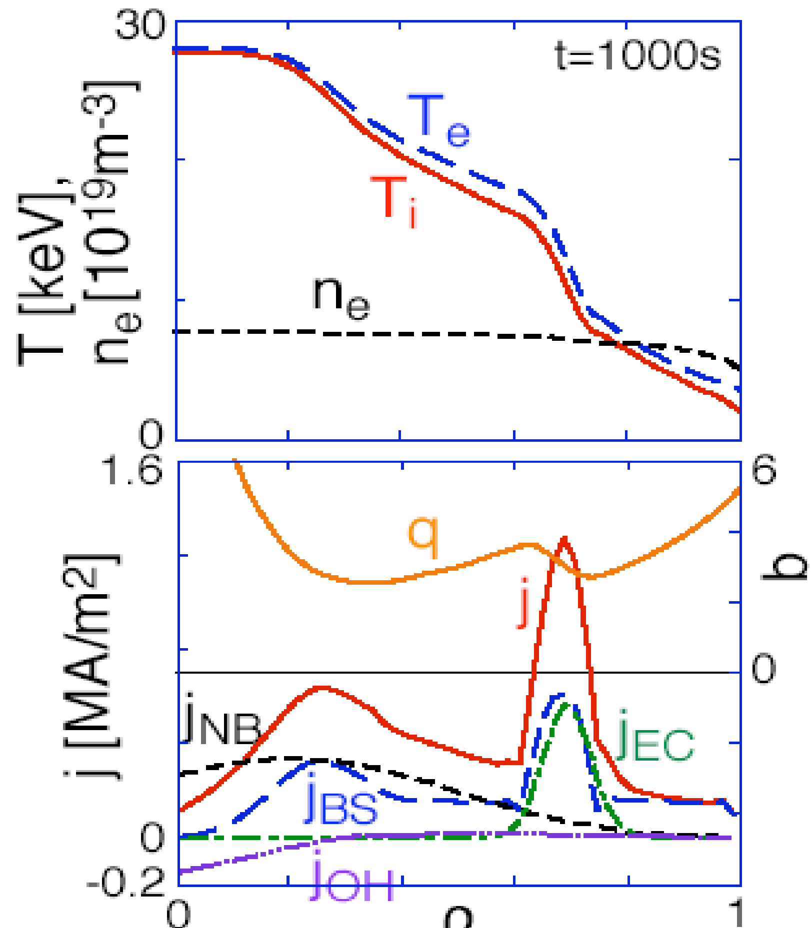
ITER steady-state simulation with weakly-reversed-shear plasma

k=0, C=1.2, w/o ExB shear stabilization

Steady-state : β_N~3.1, Q~4.6, $H_{H98(y,2)}$~1.8

No thermal instability





Simulation of ELM

1.5D Transport code: TOPICS

1D transport equations : $$\frac{\partial}{\partial t}\left(\frac{3}{2}n_j T_j\right) = \frac{\partial}{V'\partial\rho}\left(V'\left\langle|\nabla\rho|^2\right\rangle n_j \chi_j \frac{\partial T_j}{\partial\rho}\right) + P_j \quad (j = e,i)$$

1D current diffusion equation : $$\frac{\partial}{\partial t}\left(\rho\frac{\partial\Psi}{\partial\Phi}\right) = \frac{\partial}{\partial\rho}\left\{D\frac{\partial}{\partial\rho}\left(E\frac{\partial\Psi}{\partial\Phi}\right) - S(j_{BS})\right\}$$

Impurity : C^{6+}, $T_{imp}=T_i$, assumed profile Z_{eff}

$$V' = \frac{dV}{d\rho}$$

2D MHD equilibrium : Grad-Shafranov equation

$$\rho = (\Phi(\rho)/\Phi(1))^{0.5}$$

2D Equilibrium data

ELM model：enhance the transport

Eigenvalue and eigenfunction

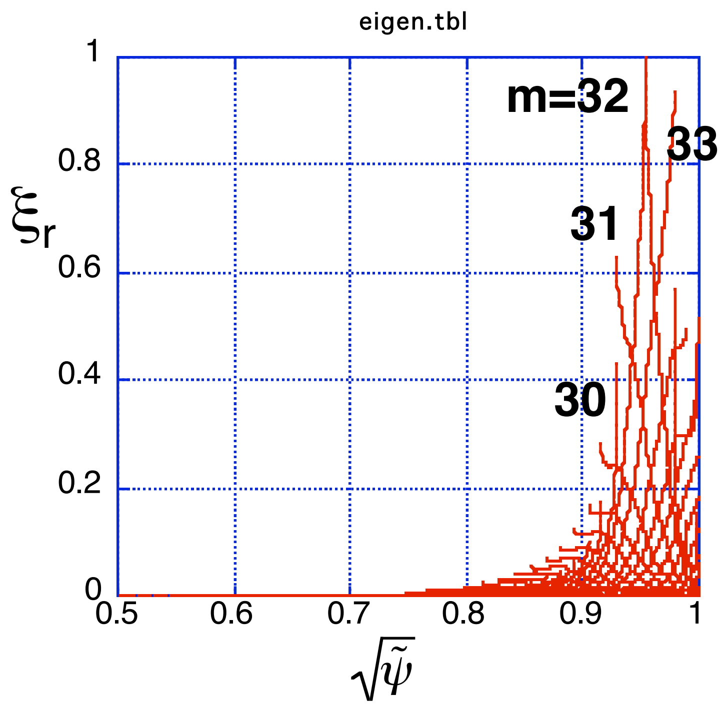
Linear stability of finite n modes (from low to high) by MARG2D

2D Newcomb equation is solved with parallel computer

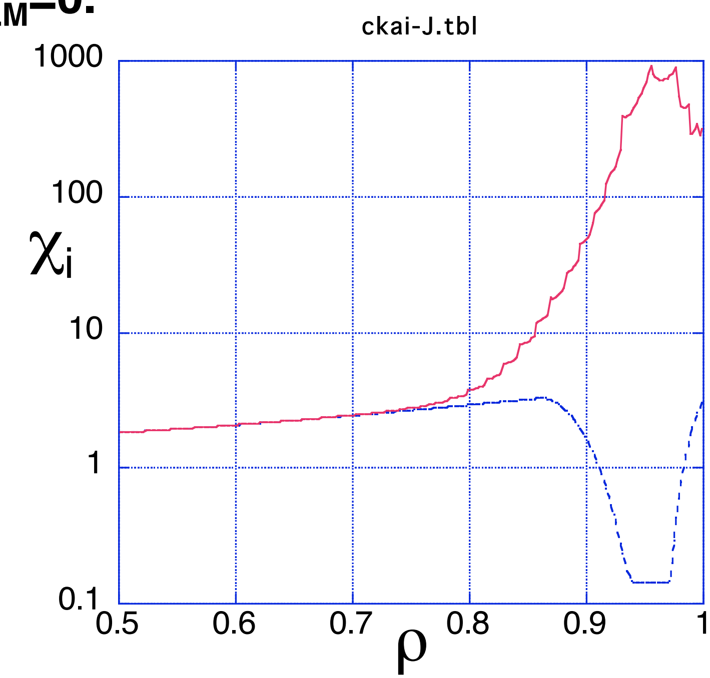
S.Tokuda, Phys. Plasmas 6 (8) 1999

ELM Model

- **The stability is examined in each iteration step of TOPICS.**
  - **When the plasma is unstable, the thermal diffusivity increases according to the eigen-function.**
  - **When the mode becomes stable, χ_{ELM}=0.**



Eigen function of unstable mode of n=7

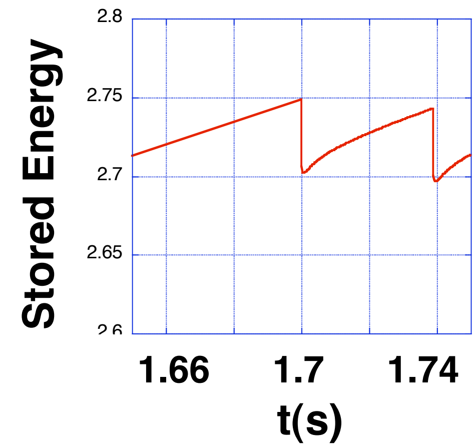


$$\chi_i = \chi_e = \chi_{neo,i} + \chi_{ano} + \chi_{ELM}$$

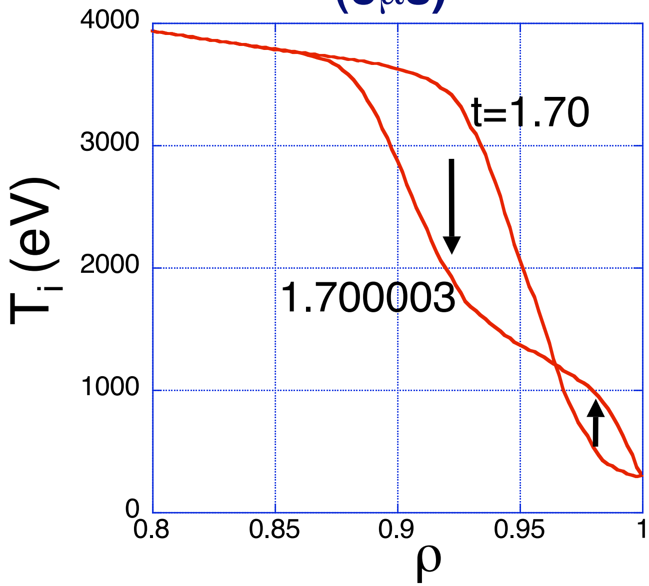
$$\chi_{ELM} = 1000[m^2/s] \times \bar{f}_{eig}(\rho)^2$$

Collapse and Recovery of T_i

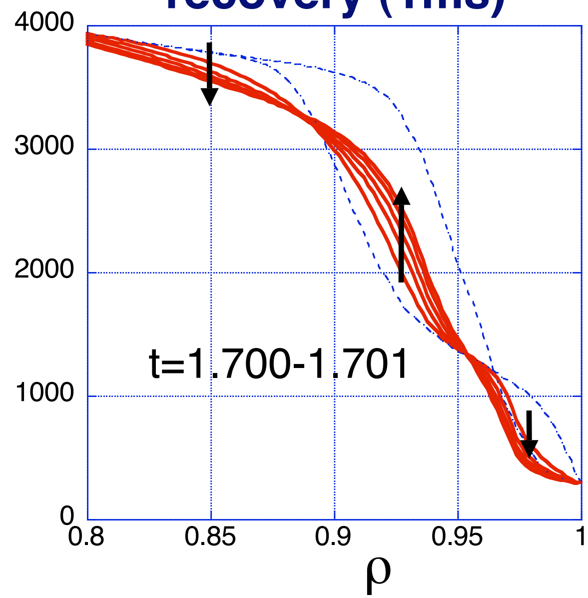
- **n=7 mode becomes unstable at 1.7. The other modes are stable (n=1-6, and 8-20).**
- **The heat conductivity increases according to the eigen function.**
- **The pedestal of the ion temperature is degraded.**
  - **The instability was checked when the shoulder of T_i relaxed by 80%. $\Delta W/W_{ped}$ ~0.23**



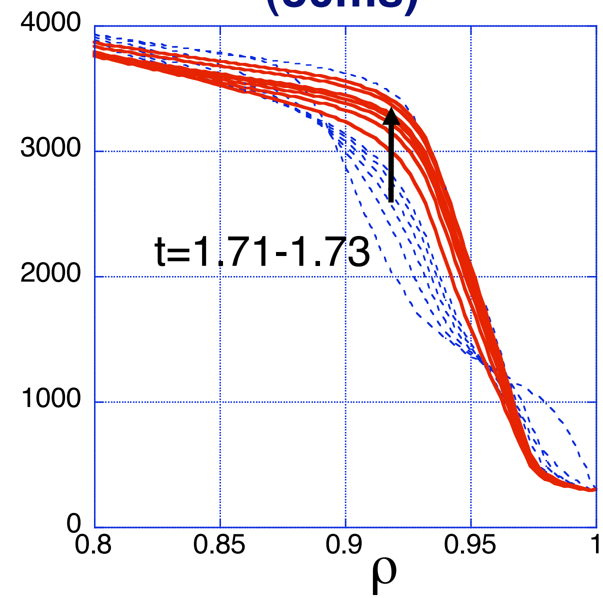
Collapse (3μs)



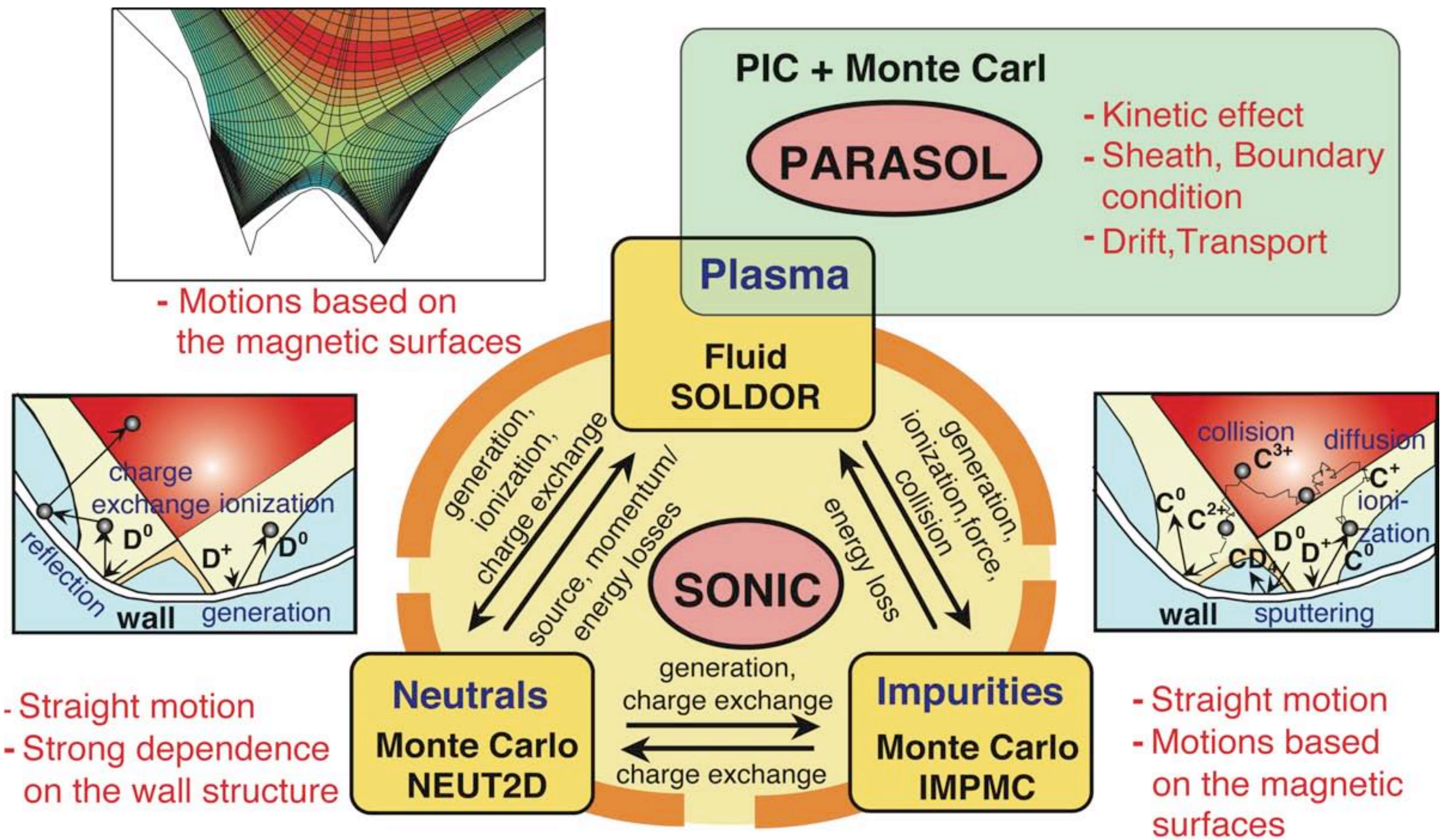
Early phase of recovery (1ms)



Recovery (30ms)



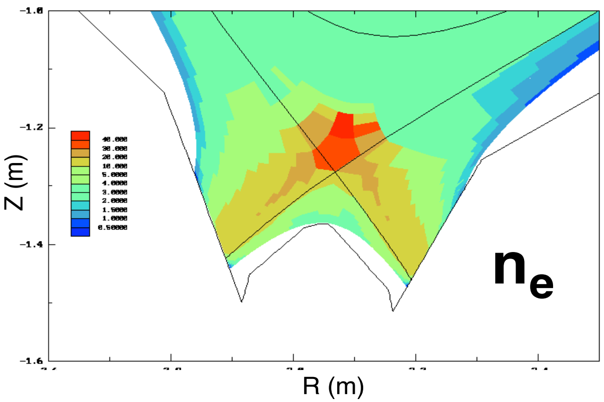
SOL/Divertor Codes in JAEA

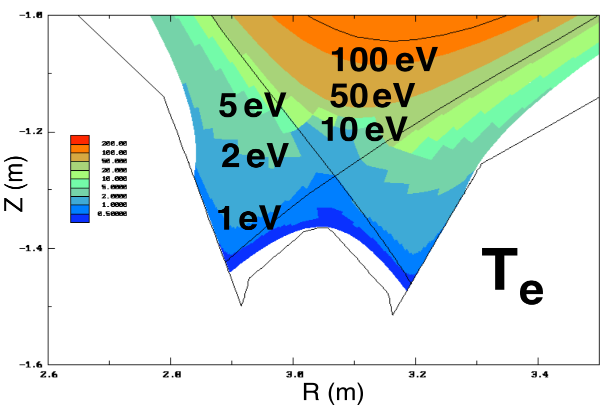


Plasma 2D Fluid Code	**SOLDOR**	} **----- Analysis/Prediction**
Neutral MC Code	**NEUT2D**	
Impurity MC Code	**IMPMC**	
Particle Simulation Code	**PARASOL**	**----- Fundamental Physics**

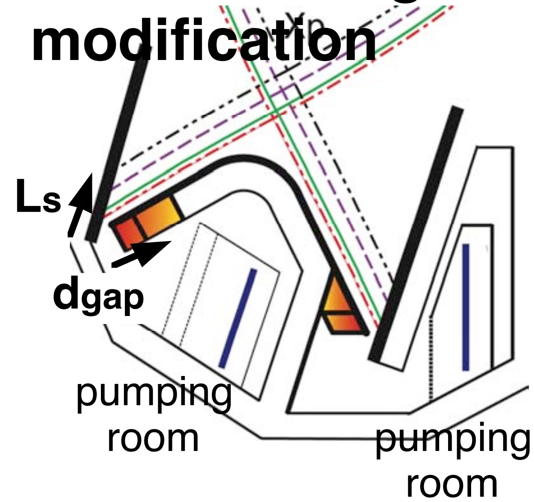
SOLDOR/NEUT2D Simulation

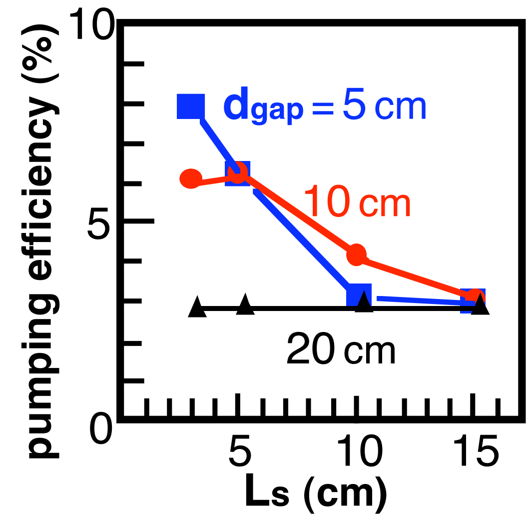
Simulation realizes X-point MARFE in JT-60U with high n_e and low T_e

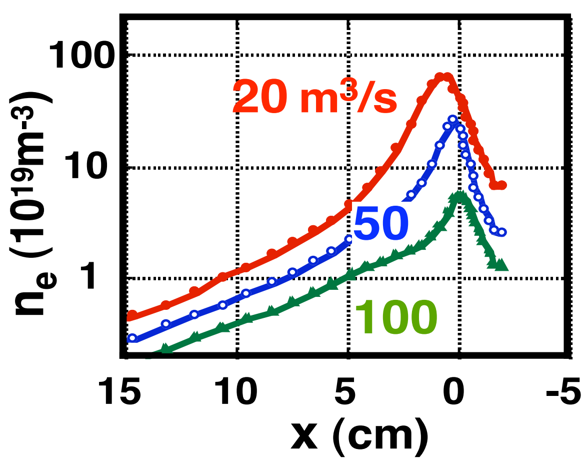




Divertor design for JT-60 modification







Pumping efficiency increases with small d_{gap} and L_s.
Divertor control by pumping is possible.

SOLDOR/NEUT2D is now used for the ST divertor design by Kyushu university.

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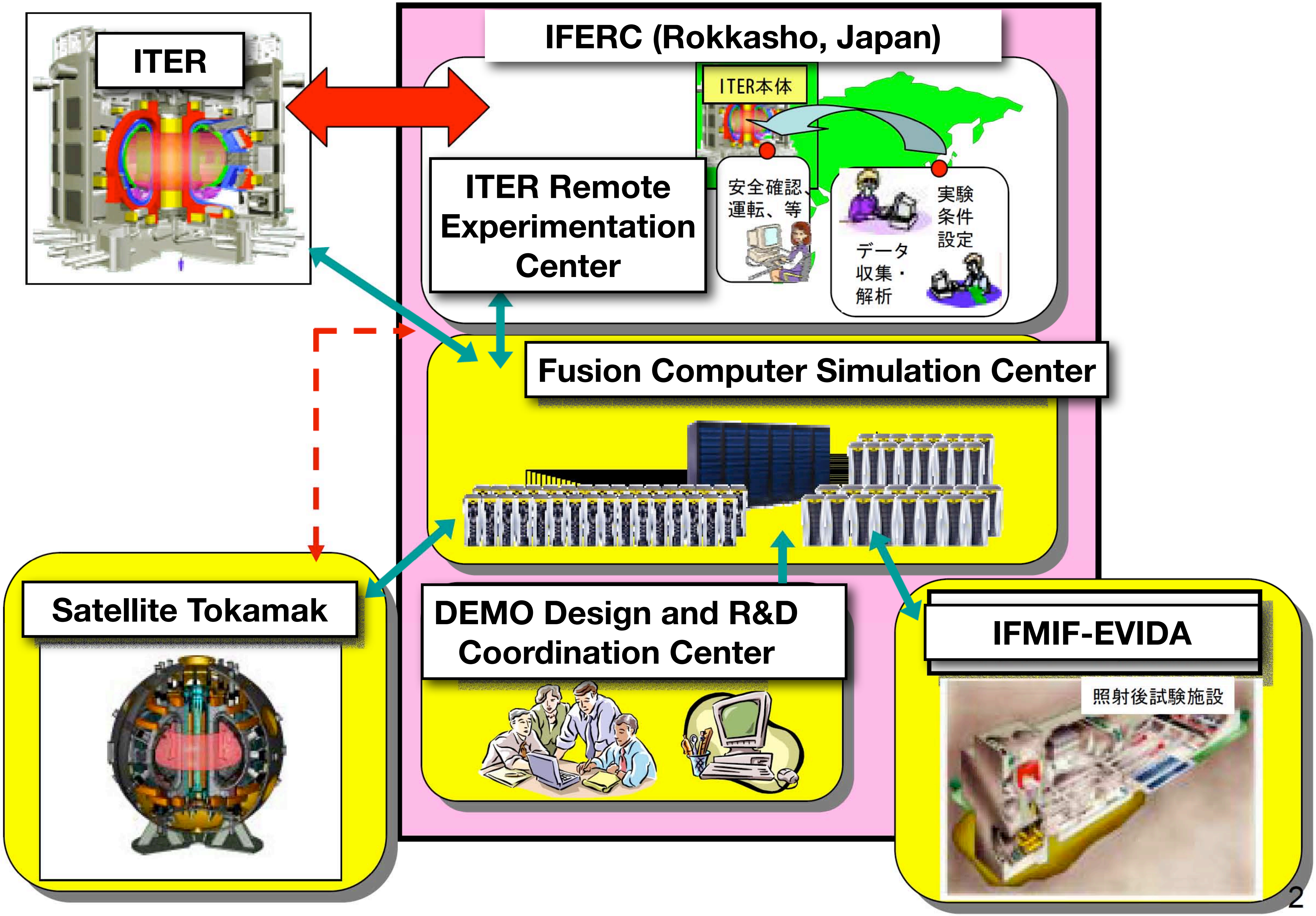
ITER-BA computer simulation center

- **ITER-BA**: Broader Approach activites in support of ITER
  - **Agreement between Japan and EURATOM**:
    — to be established soon.
- **Activites**: (under negociation)
  - **Satellite Tokamak Programme**:
    — JT-60SA (Advanced Superconducting Tokamak)
  - **IFMIF-EVEDA**:
    — Engineering Validation and Engineering Design Activities for the International Fusion Materials Irradiation Facility
  - **IFERC**: International Fusion Energy Research Center
    — DEMO Design and R&D Coordination Center
    — **Fusion Computer Simulation Center** (2012~)
    — ITER Remote Experimentation Center

International Fusion Energy Research Center



Summary

- **Computer simulation** is playing a key role in fusion research in Japan.
- **Principle based simulations** are being promoted as **a hierarchy model based approach** in NIFS and the **NEXT** project in JAEA.
- **Integrated simulations** are forwarded by **BPSI**; **TASK** in Kyoto Univ., **TOPICS** in JAEA, and **TASK/H** in NIFS are under development in collaboration with each other.
- We welcome **international collaboration** with Chinese fusion simulation activities.