第１２回若手研究会
那珂核融合研究所
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# 原子力機構におけるトカマク統合コードの開発と最近の研究成果

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原子力機構

# Introduction

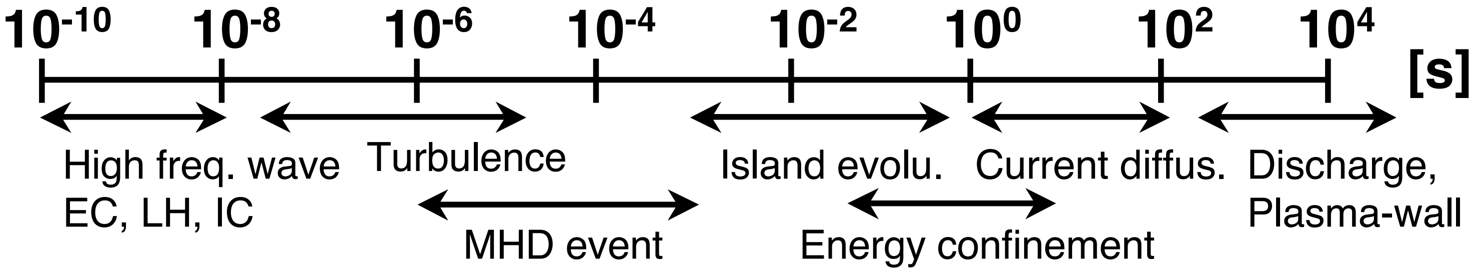
## Issues of fusion burning plasmas:
## Control of plasmas with strong complexity and autonomy

- Multi-scale Physics
  - Consit of the wide spacial scale and the time scale
  - Consist of complexibility and self-organization
- Recurring Process
  - Bulk plasma determines a-heating profile, α-heating profile determines the bulk plasma profile
  - Nonlinearity: multi equilibrium point, bifurcation, discontinuity
- Steady-state control
  - α-heating＞external heating: Reduction of heating power for the control
  - Bootstrap current＞externally driven current: Reduction of CD and momentum input for the control
  - Existence of the steady state solution, controllability, stiffness

# Background

- To progress the research of burning plasma , it is necessary to understand complex features of the advanced tokamak plasmas.
  - – Because, in the steady state, plasma has very wide time scale and spatial scale, and it has complex physics such as turbulence, transport, MHD, wave-particle interaction, plasma-wall interaction, atomic and molecular physics, and so on

- Timescales



$10^{-10}$ $10^{-8}$ $10^{-6}$ $10^{-4}$ $10^{-2}$ $10^{0}$ $10^{2}$ $10^{4}$ [s]

High freq. wave EC, LH, IC

Turbulence

MHD event

Island evolu.

Energy confinement

Current diffus.

Discharge, Plasma-wall

- Exploration and understand of the complex plasma are big issues.
  - High confinement, high beta, high bootstrap fraction, high radiation fraction, control of ash and impurity, $\alpha$-heating, etc.

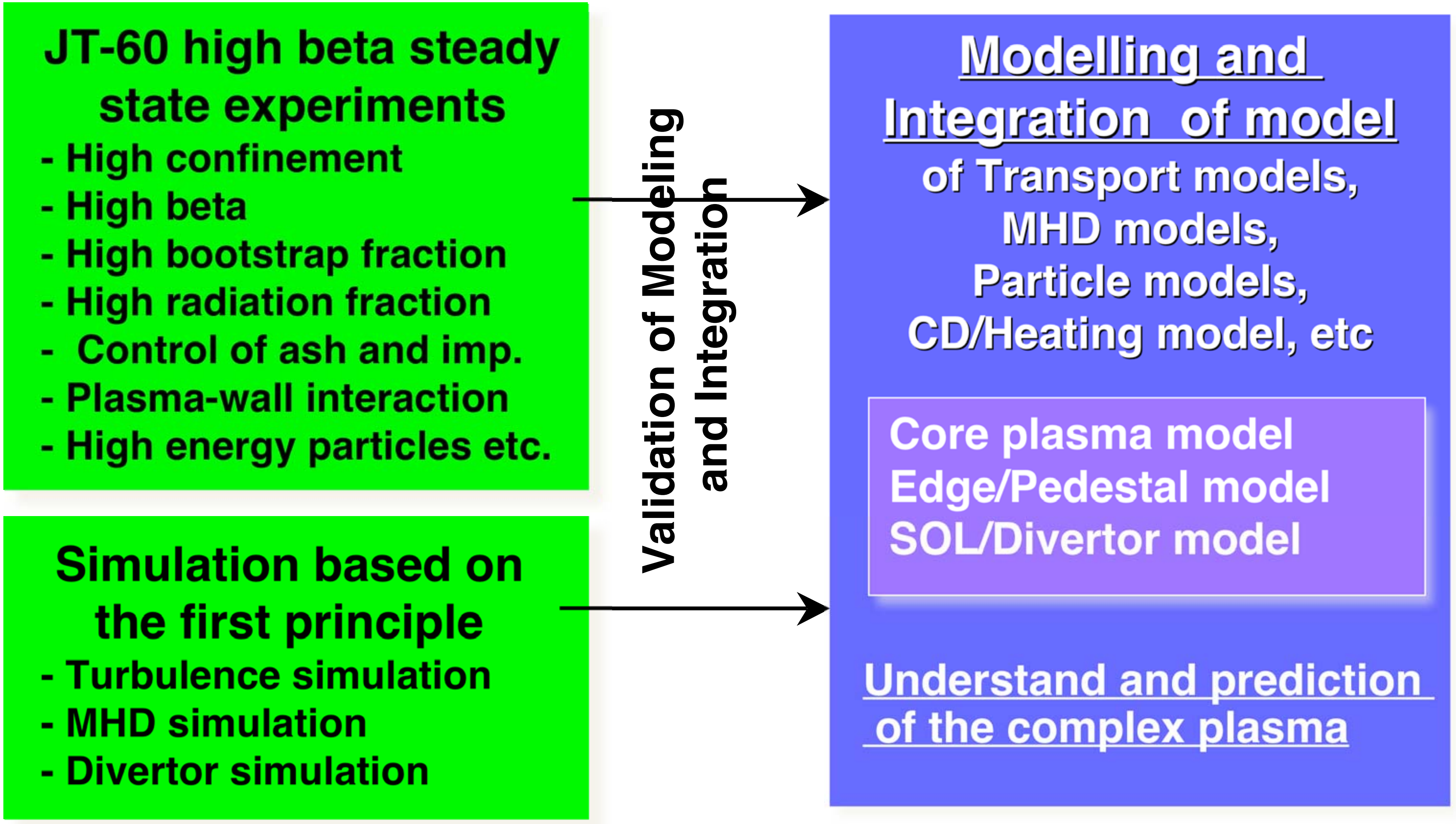
Control of the complex plasma are also serious issues.

  - Strong coupling of each physics mechanism, i.e. autonomous plasmas

Modeling and integration of models are useful means for the understand and the prediction of the burning plasma.

# Strategy of Modeling / Integration of model

**To make the integrated model, validation is necessary based on the fundamental researches of experiment and simulation.**



**JT-60 high beta steady state experiments**

- High confinement
- High beta
- High bootstrap fraction
- High radiation fraction
- Control of ash and imp.
- Plasma-wall interaction
- High energy particles etc.

**Simulation based on the first principle**

- Turbulence simulation
- MHD simulation
- Divertor simulation

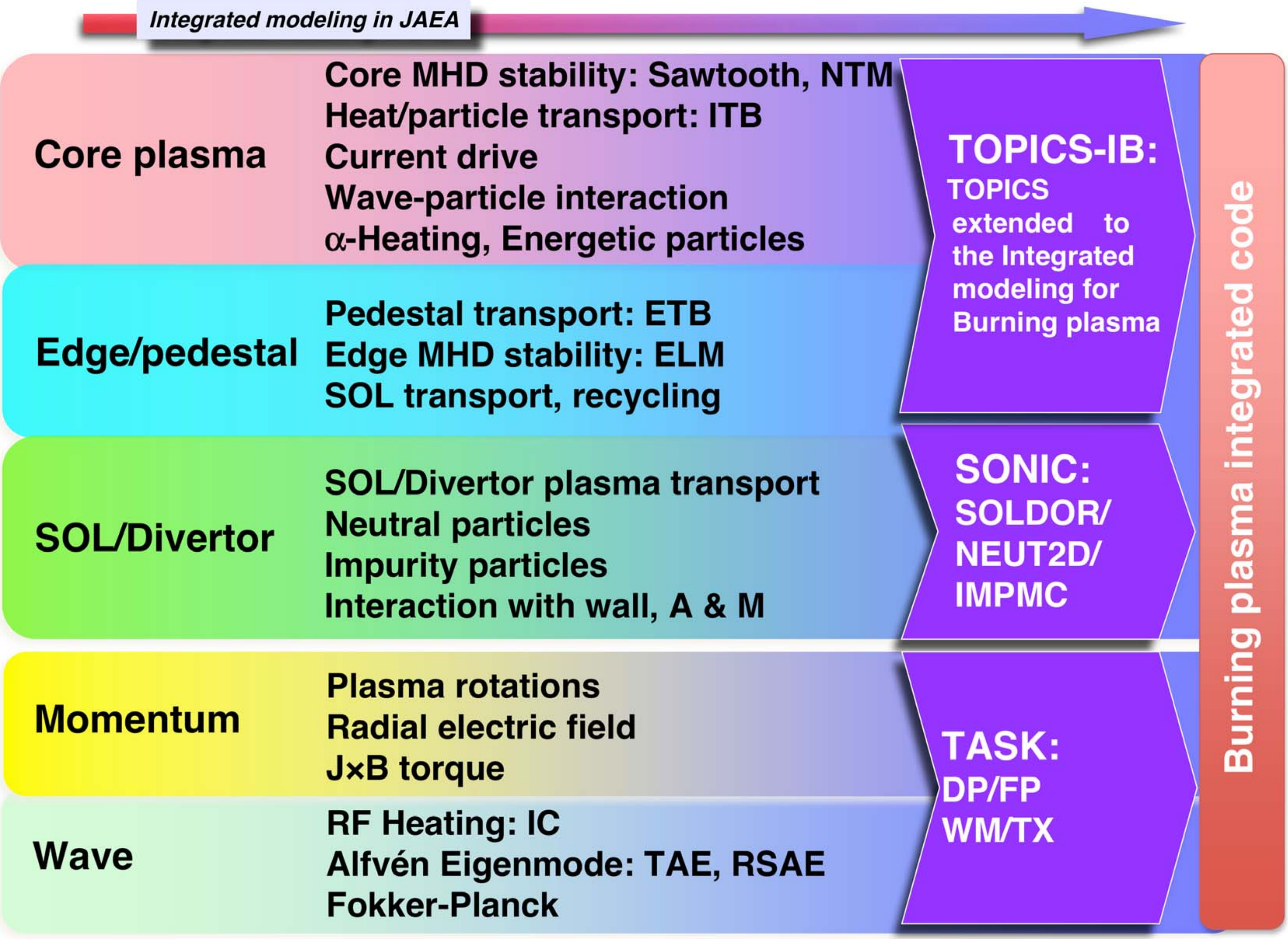
Validation of Modeling and Integration

**Modelling and Integration of model**

of Transport models,
MHD models,
Particle models,
CD/Heating model, etc

Core plasma model
Edge/Pedestal model
SOL/Divertor model

**Understand and prediction of the complex plasma**



*Integrated modeling in JAEA*

**Core plasma**
- Core MHD stability: Sawtooth, NTM
- Heat/particle transport: ITB
- Current drive
- Wave-particle interaction
- α-Heating, Energetic particles

**Edge/pedestal**
- Pedestal transport: ETB
- Edge MHD stability: ELM
- SOL transport, recycling

**SOL/Divertor**
- SOL/Divertor plasma transport
- Neutral particles
- Impurity particles
- Interaction with wall, A & M

**Momentum**
- Plasma rotations
- Radial electric field
- J×B torque

**Wave**
- RF Heating: IC
- Alfvén Eigenmode: TAE, RSAE
- Fokker-Planck

**TOPICS-IB:**
TOPICS extended to the Integrated modeling for Burning plasma

**SONIC:**
SOLDOR/
NEUT2D/
IMPMC

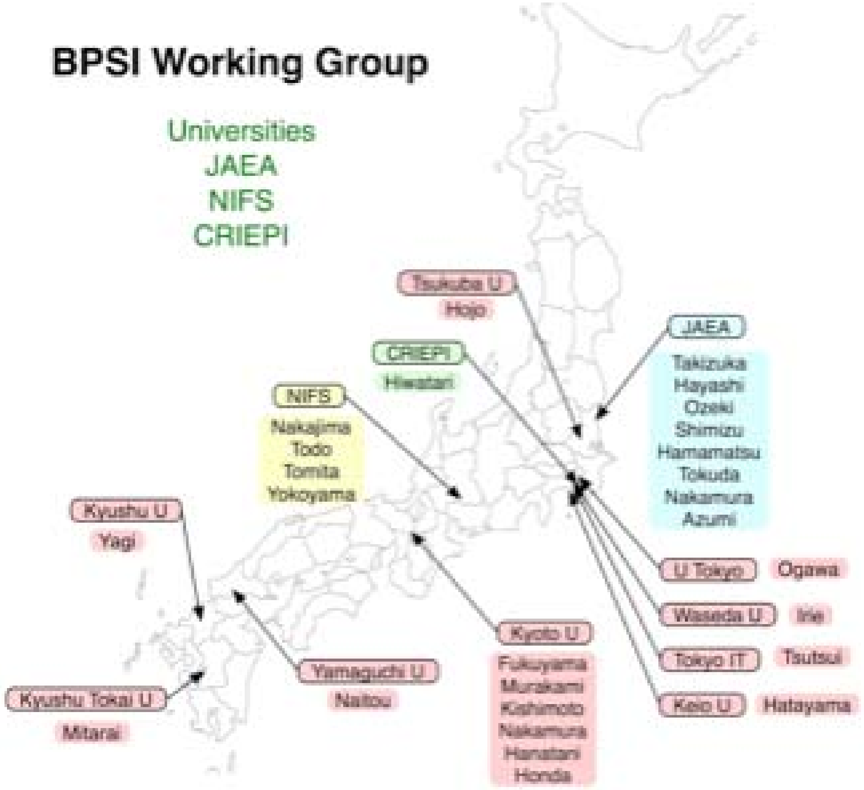
**TASK:**
DP/FP
WM/TX

**Burning plasma integrated code**

# 核燃焼プラズマ統合コード開発構想

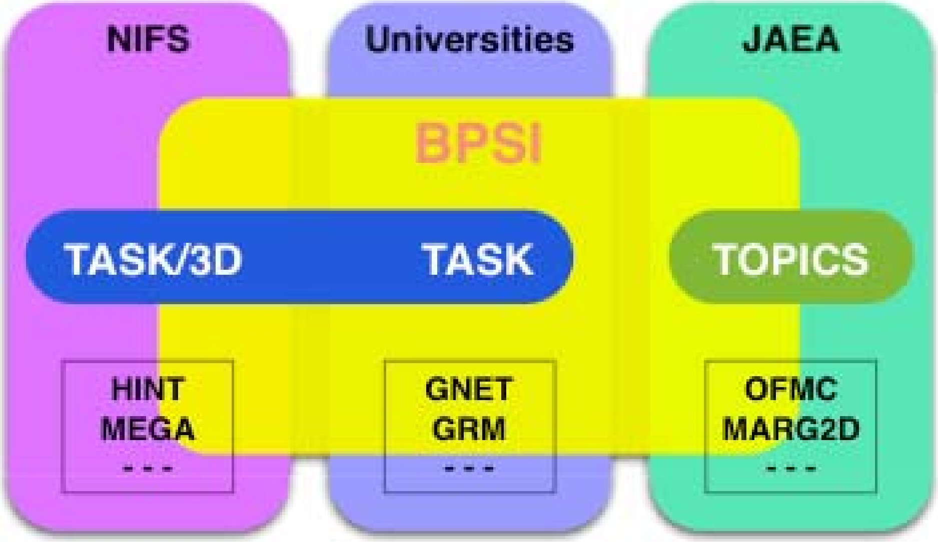
**BPSI: Burning Plasma Simulation Initiative**

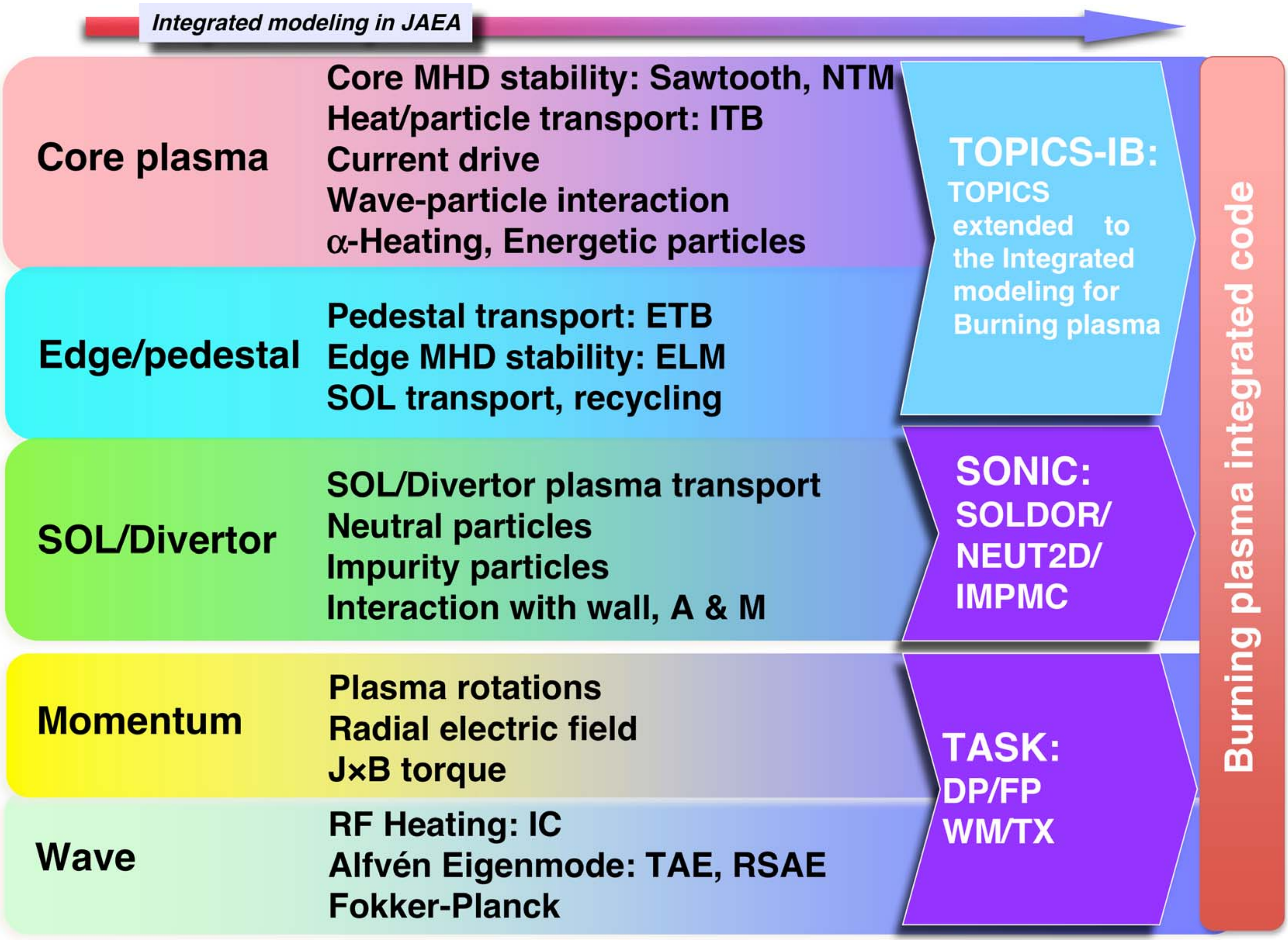
大学，核融合研，原子力機構等の研究協力



BPSI Working Group

## 統合コード開発





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**Burning plasma integrated code**

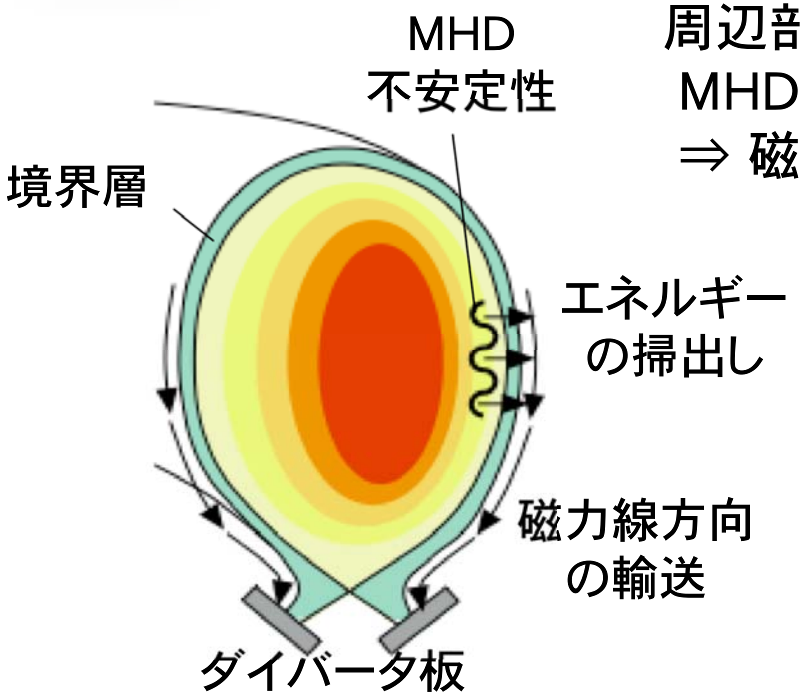
# TOPICS-IB (TOPICS extended to Integrated simulation for Burning plasmas)

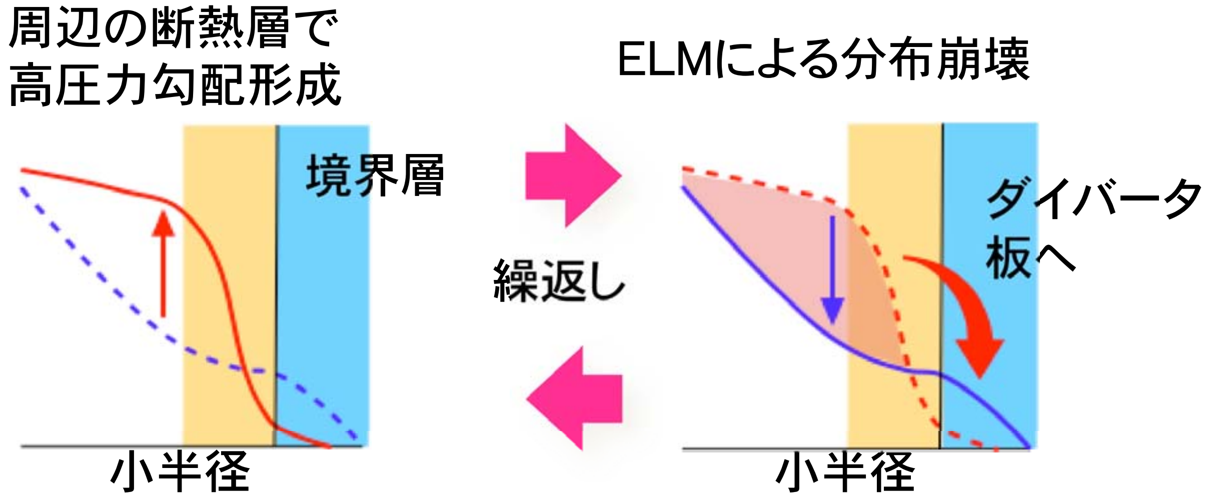
- TOkamak Prediction and Interpretation Code System
  - 1D transport & 2D MHD equilibrium
  - Time-dependent / Steady-state analysis of JT-60U experiment
  - Simulation with transport model
    Neoclassical : MI method or NCLASS, Anomalous : CDBM, GLF23, MMM95
- Components and Related codes
  - NB & High energy particle : 1D or 2D FP, 3D Monte-Carlo (OFMC)
  - EC : Ray tracing & Relativistic FP (EC-Hamamatsu)
  - MHD : Kink / Ballooning / Peeling (MARG2D)
  - Impurity : 1D transport (IMPACT), 2D Monte-Carlo (IMPMC)
  - Neutral : 2D Monte-Carlo
  - Radiation : Synchrotron (CYTRAN)
  - SOL / Div. : Five-point model (D5PM), 2D Fluid & Monte-Carlo (SONIC)
- Recent works
  - **Core-SOL-div. integration for ELM study (loss & cycle) (Hayashi, IAEA08)**
  - **Integration with 1d1v FP code of $\alpha$ particles (Ozeki, Hamamatsu, JSPF08)**

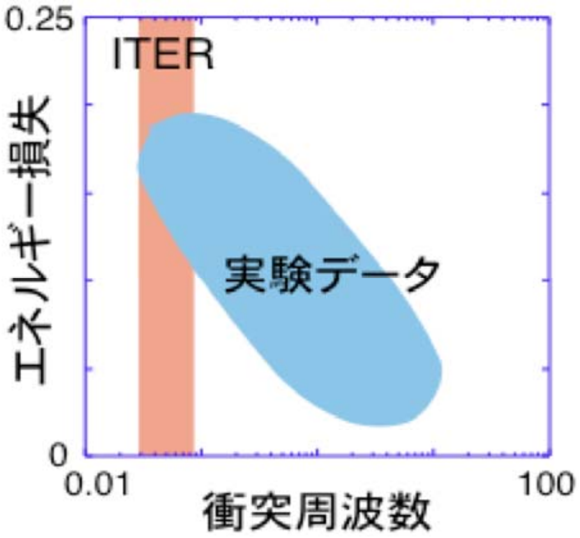
# 周辺部局在モードによるエネルギー損失

**背景**　核融合炉への課題: プラズマ閉込め容器への熱負荷の低減

周辺部局在モード（Edge Localized Mode ; ELM）
MHD不安定性による分布崩壊 ⇒ 周期的なエネルギー放出
⇒ 磁力線方向の輸送 ⇒ ダイバータ板の損耗



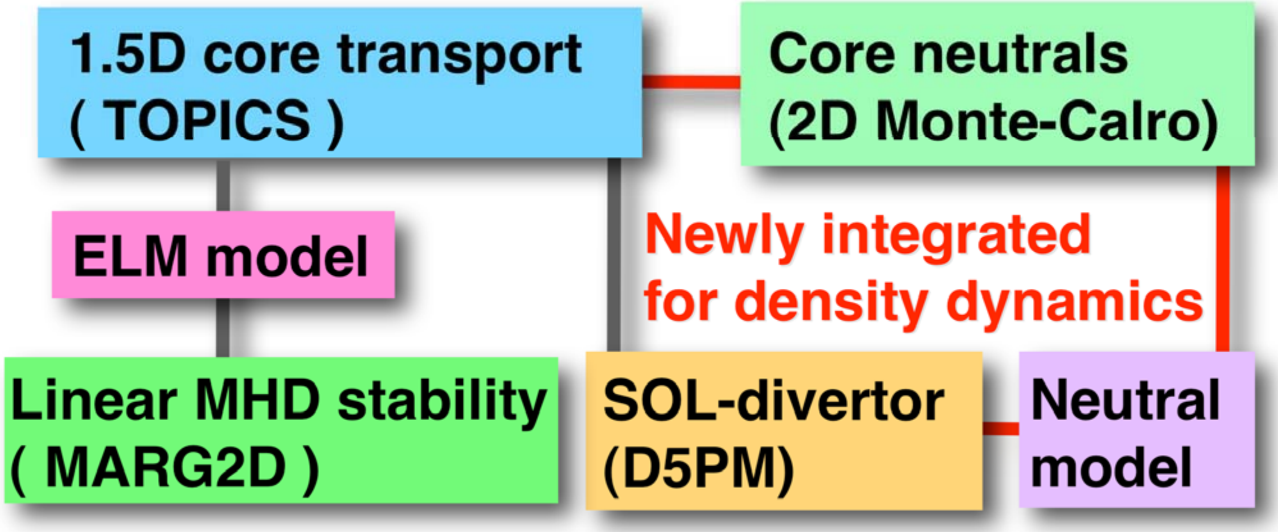




ELMによるエネルギー損失 :
多装置の実験データは、プラズマの衝突周波数に依存
ITERの高温（低衝突）プラズマで過大な損失?

**衝突周波数依存性の発生機構が未解明の課題**

# Simulation of ELM energy loss and cycle



**1.5D core transport ( TOPICS )**

**Core neutrals (2D Monte-Calro)**

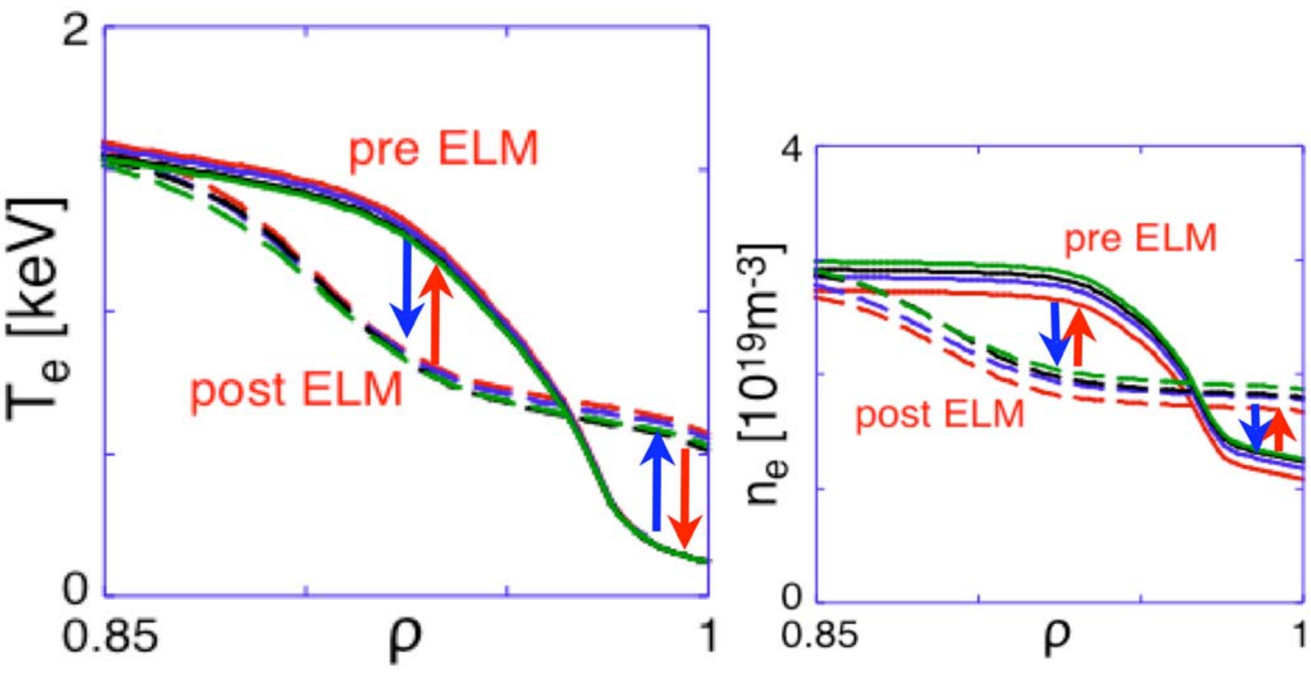
**ELM model**

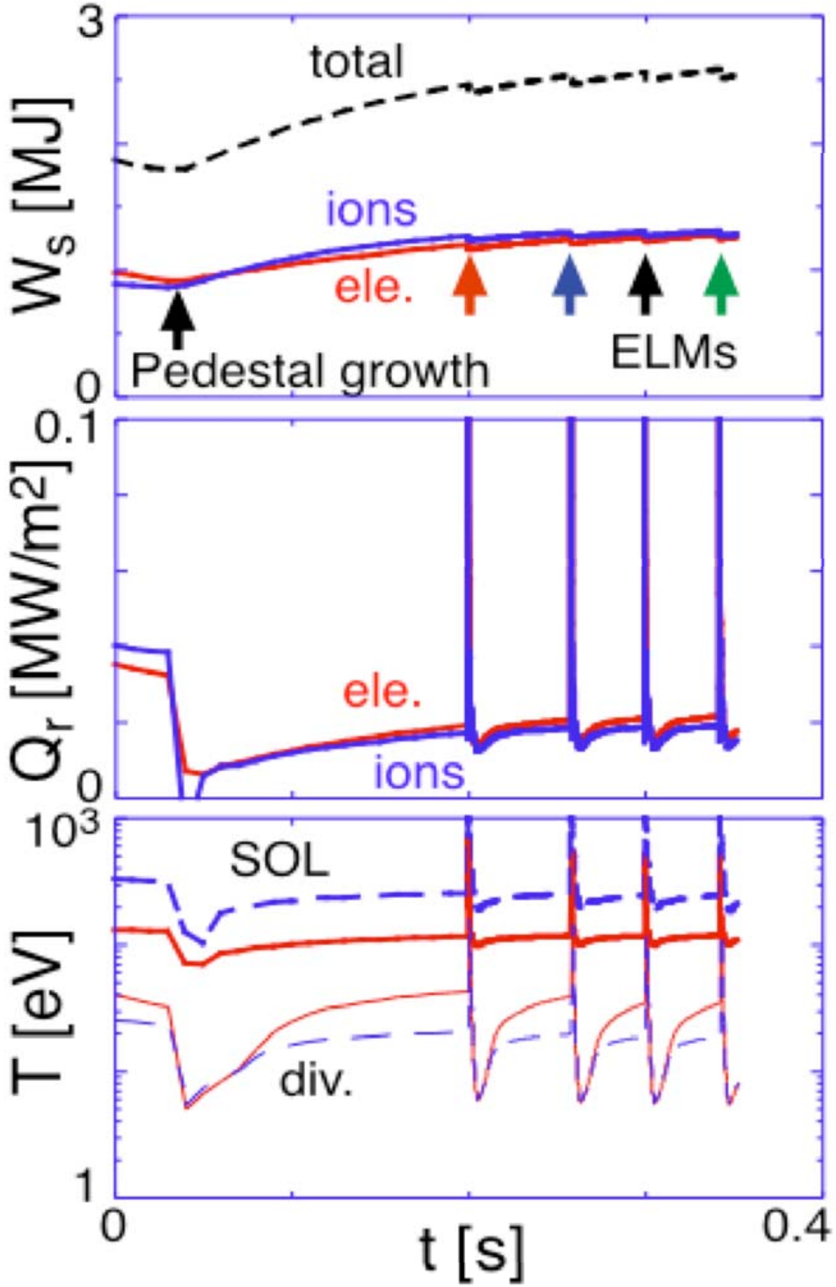
**Newly integrated for density dynamics**

**Linear MHD stability ( MARG2D )**

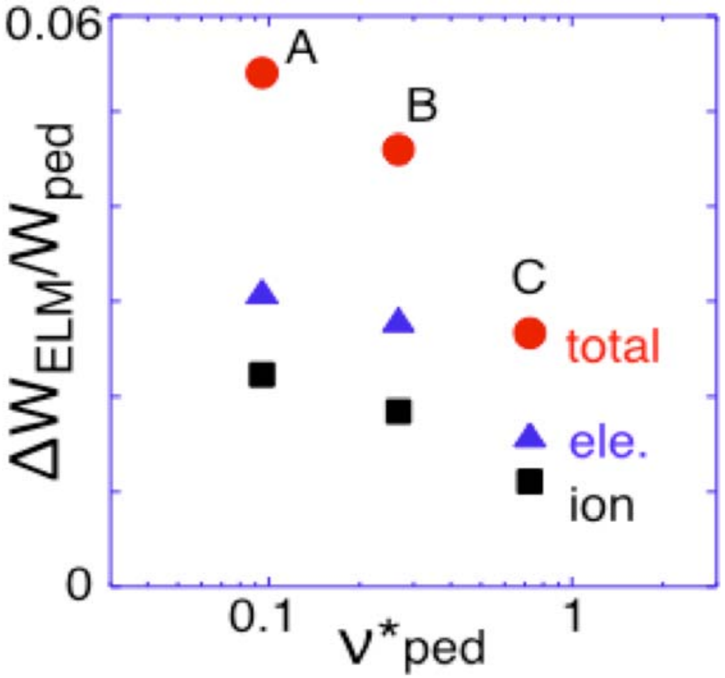
**SOL-divertor (D5PM)**

**Neutral model**





# Integrated modeling reproduces the collisionality dependence of ELM energy loss.



ELM energy loss in the follwoing ELMs deviates a little from that at first ELM, but the collisionality dependence is almost the same.

As found in the first ELM (H-modeWS07), the following physics cause the dependence.

- Electron : Bootstrap current broadens the region of ELM enhanced transport and SOL parallel conductive transport decreases the SOL temperature in the low collisionality. (NF07)

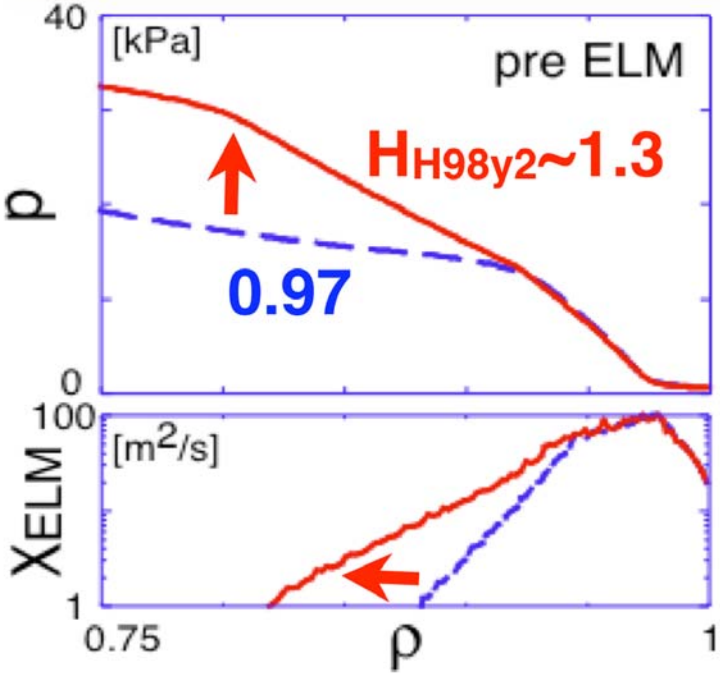
- Ion : $T_i > T_e$ in the low collisionality due to the ineffectiveness of equipartition, which enhances ion convective and CX losses.

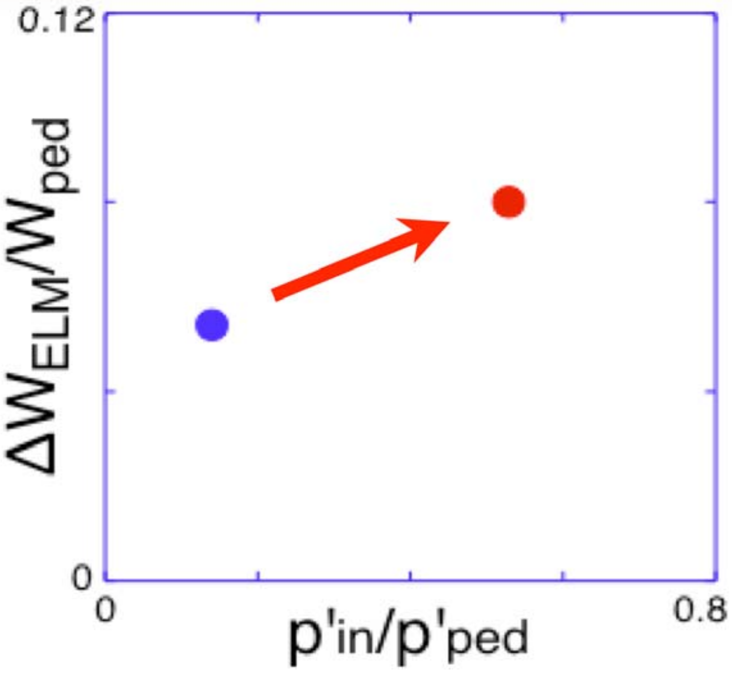
Reduction of total energy loss is comparable with that in experiments.

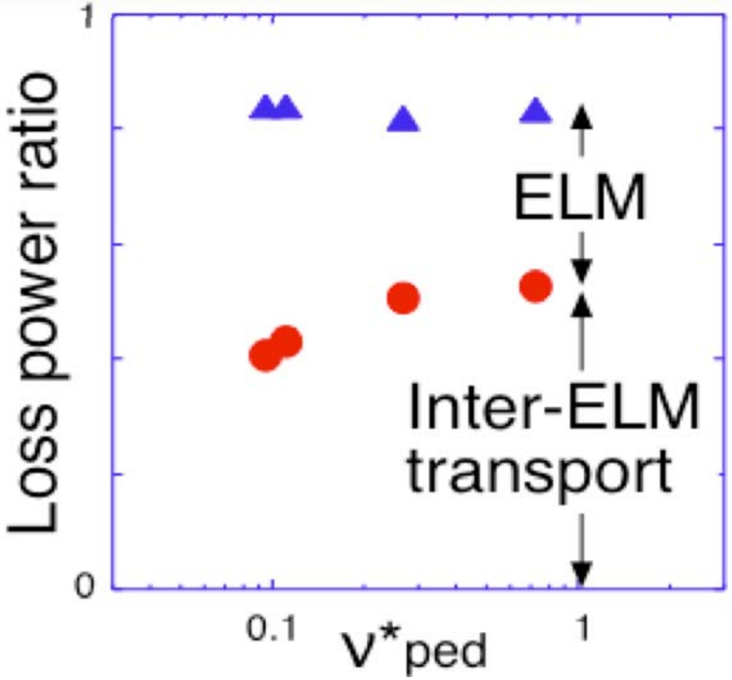
# Integrated Simulation of ELM Energy Loss and Cycle in Improved H-mode Plasmas ( Hayashi, IAEA08 )

- **Integrated code TOPICS-IB** clarified that **steep pressure gradient inside the pedestal top** broadens the region of ELM enhanced transport and **enhances the ELM energy loss**.

- Transport model of **pedestal neoclassical transport connected to SOL parallel transport** reproduces the **experimentally observed collisionality dependence of inter-ELM transport**. Inter-ELM energy confinement time agrees with JT-60U scaling.

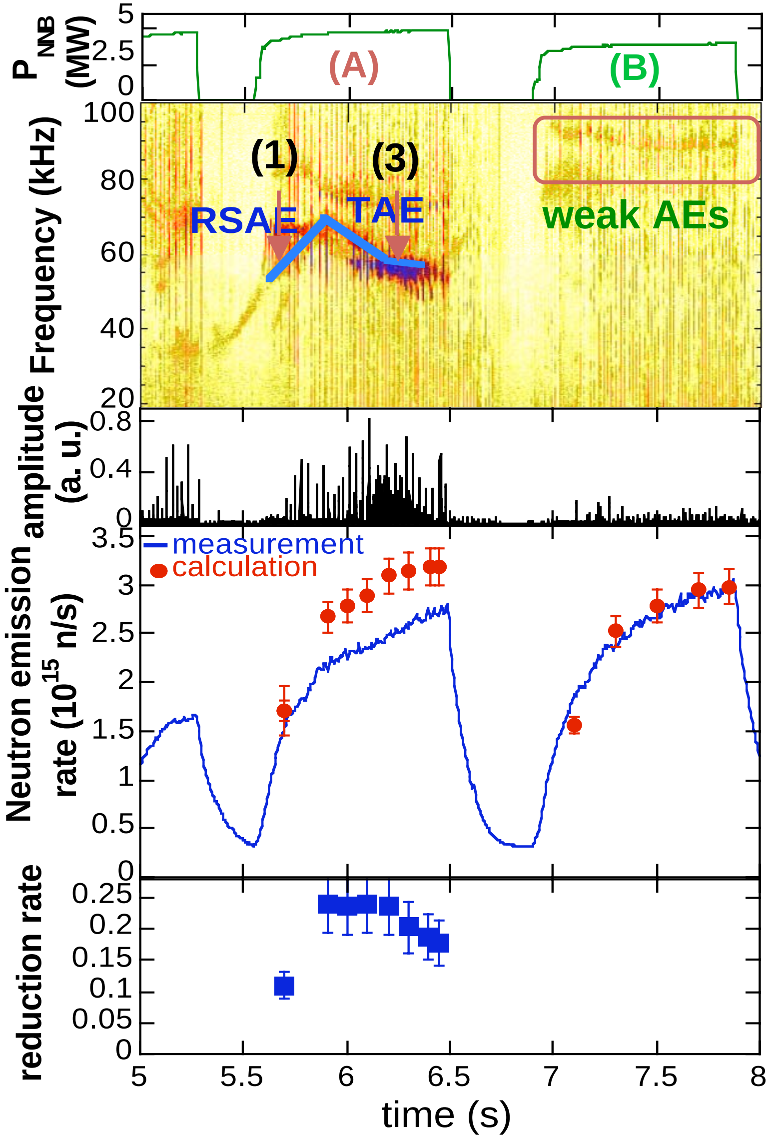






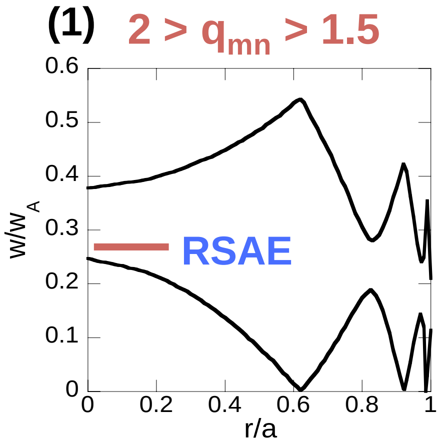
# Energetic particle loss by AE modes

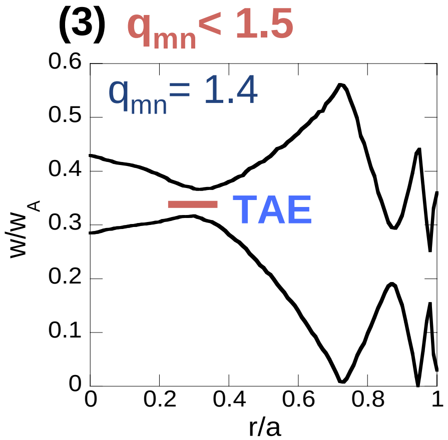
**E46078 1.0MA/1.7T, $E_{NNB}$~390 (keV)**



[M.Ishikawa, IAEA, FEC, 2006]

## AE modes in a weak shear plasma





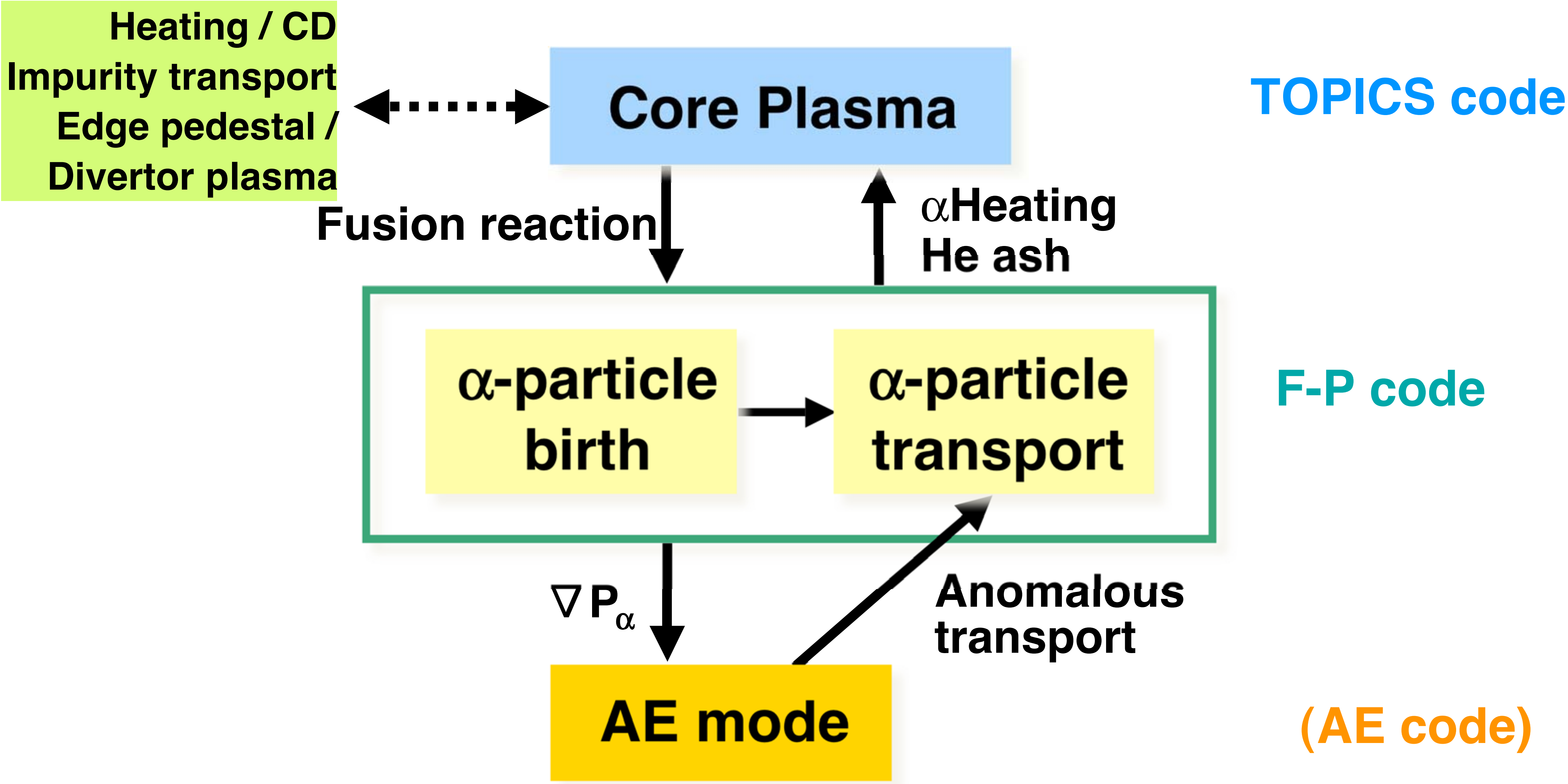
**(A) Sn reduced in 20~30% when AE modes existed.**
**Degradation of high energy particles**

**(B) Measured Sn was close to the OFMC calculation: ~ classical confinement**

**Reduction rate of Sn increased in AE mode flucuation**

**Plausible candidate is MHD resonance particle loss.**

# Simulation of Autonomous and Recurrence Process



Heating / CD
Impurity transport
Edge pedestal /
Divertor plasma

Core Plasma

TOPICS code

Fusion reaction

αHeating
He ash

α-particle birth

α-particle transport

F-P code

$\nabla P_\alpha$

Anomalous transport

AE mode

(AE code)

# α-particle birth and transport model

by K.Hamamatsu

$f(v,\rho,t)$ **: Velocity distribution function of alphas** ***v*** **: velocity, ρ : minor radius**

$$\frac{\partial}{\partial t} f(v,\rho,t) + \frac{1}{\rho}\frac{\partial}{\partial\rho}\left[\rho\left(-D(v,\rho)\frac{\partial f}{\partial\rho} + V_{AN}(v,\rho) f\right)\right] = \sum_j C_j(f) + S(v,\rho) - L(f)$$

$$D(v,\rho) = D_{NC}(v,\rho) + D_{AN}(v,\rho)$$

**2D Fokker-Planck Equation**

○ $D_{NC}(v,\rho)$ **: Neo-classical like diffusion**

$$D_{NC}(v,\rho) = \sqrt{\frac{2\varepsilon}{1+\varepsilon}\frac{\Delta_b^2}{\tau_{eff}}}, \Delta_b = \frac{2v\cos\alpha}{\Omega_p}, \tau_{eff} = \frac{4\varepsilon}{1+\varepsilon}\tau_\perp(v), \varepsilon = \frac{\rho}{R_0}, \tau_\perp(v)$$

**: Pitch angle scat. time**

○ $D_{AN}(v,\rho)$ & $V_{AN}(v,\rho)$ **: Anomalous diffusion & convection**

**model of the resonance with MHD instability**

○ $C_j(f)$ **: Collision term colliding with *j*-th bulk plasma**

***n*$_s$*(ρ)* and *T*$_s$*(ρ)* are calculated by TOPICS-IB**

○ $S(v,\rho)$ **: Particle source by fusion reaction and NBI**

○ $L(f)$ **: Loss term removes slowed down particles**

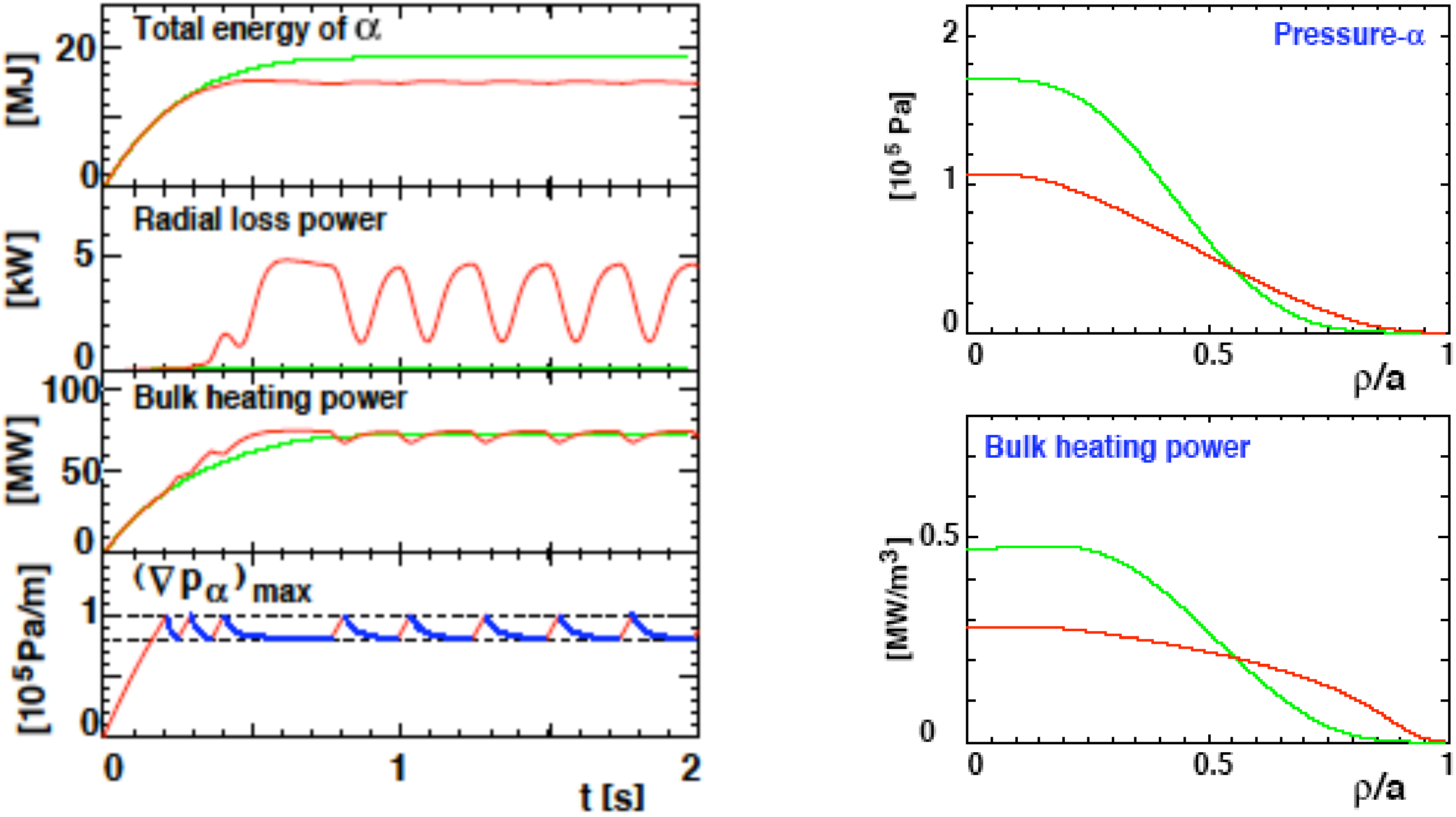
○ $$L(f) = \frac{f(v,\rho,t)}{\tau_{th}(\rho)}\exp\left(-\frac{m_\alpha v^2}{\lambda T_{ash}(\rho)}\right),$$

**$\lambda$ is constant. ⇒ $\lambda$=3 in this case**

**$\tau_{th}(\rho)$ : thermal collison time**

# Simulation of F-P equation for fixed background

- **Effects of the anomalous transport on the $\alpha$-particle pressure/heating**
- **Assumption: : neo-classical like $\alpha$-diffusion, the anomalous by the MHD fluctuation and zero flow velocity**



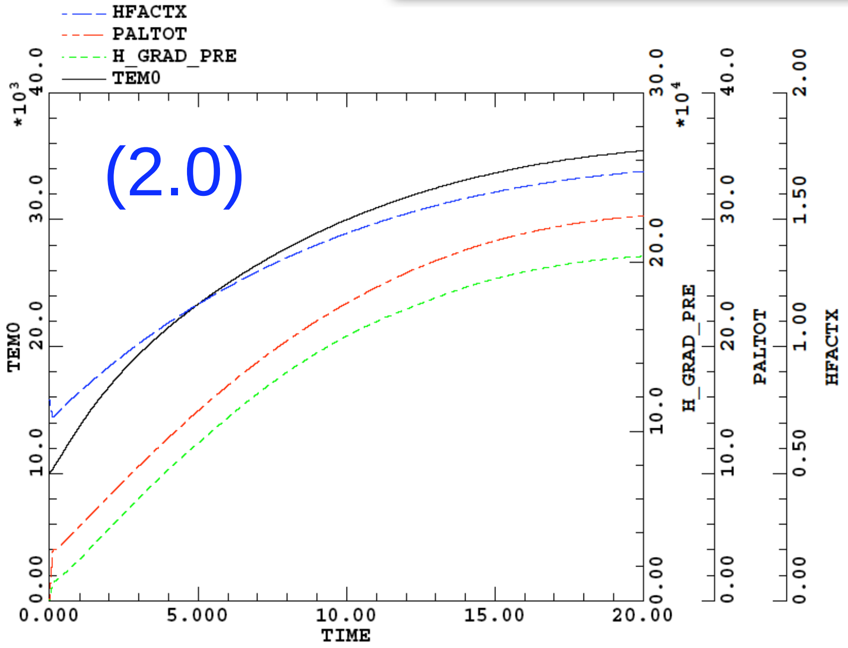
**•Time trace and profiles for the simulation with (red) and without(green) anomalous**

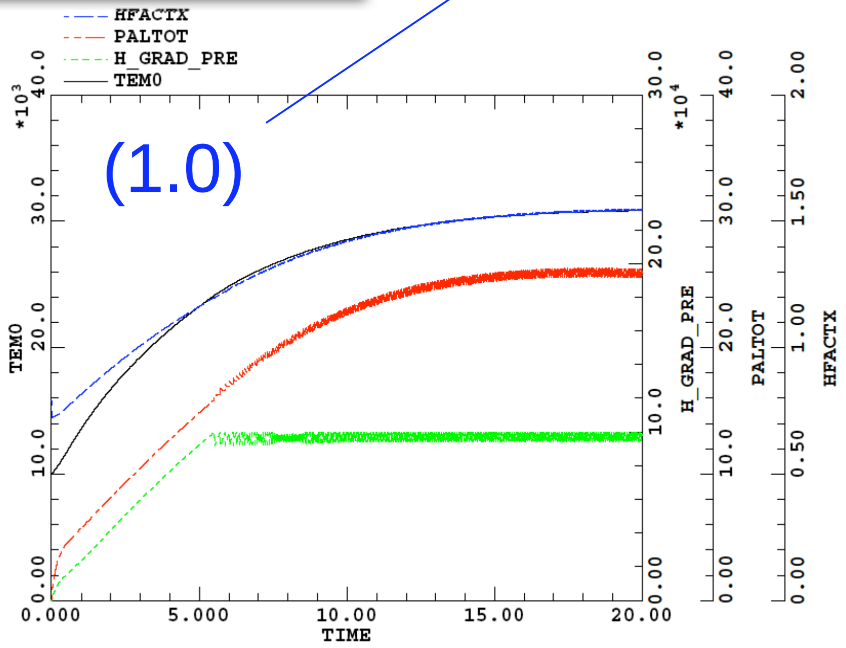
**On of anomalous:** $$\left|\frac{\partial p_\alpha}{\partial \rho}\right|_{\max} \geqq \left.\frac{\partial p_\alpha}{\partial \rho}\right|_{on}$$

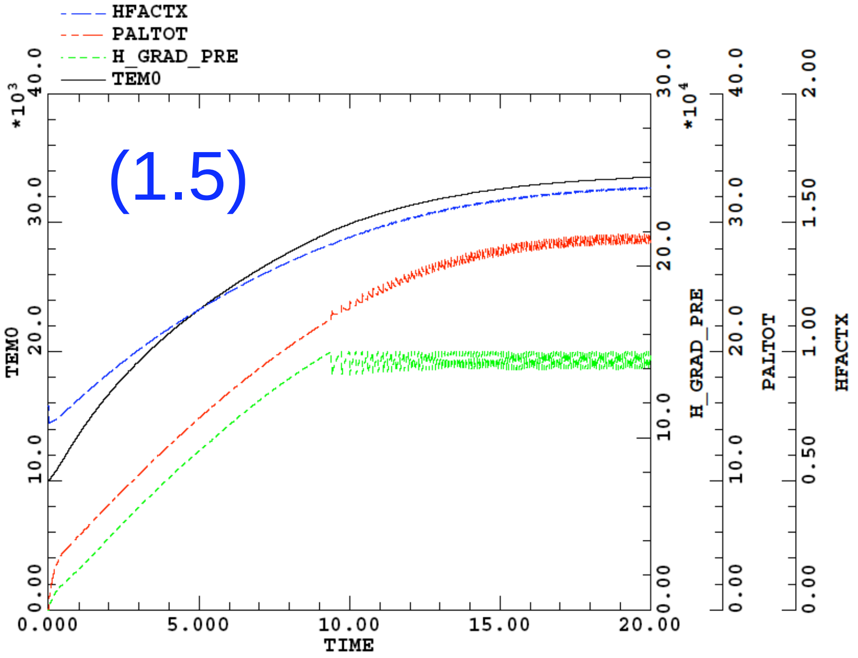
**Off of anomalous:** $$\left|\frac{\partial p_\alpha}{\partial \rho}\right|_{\max} \leqq \left.\frac{\partial p_\alpha}{\partial \rho}\right|_{off}$$

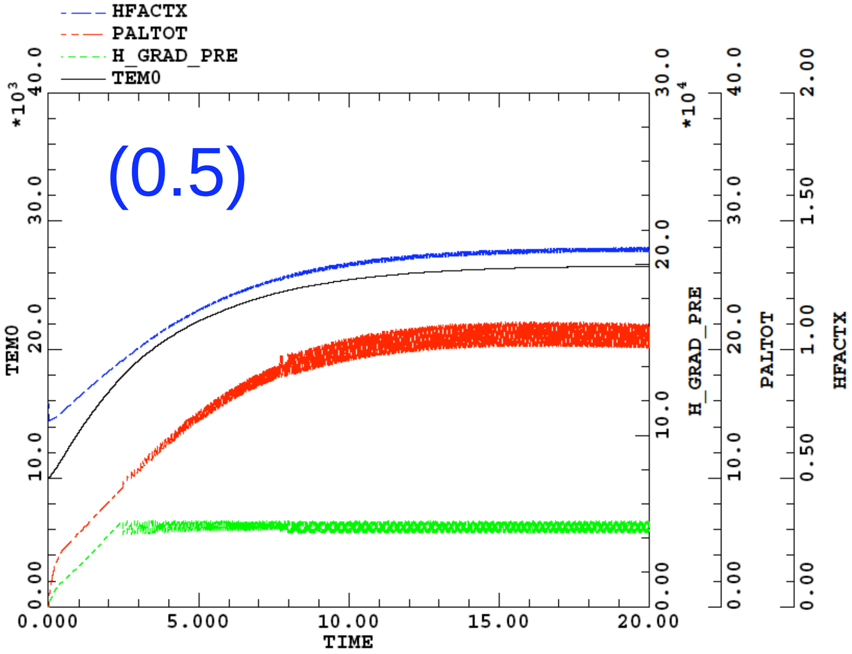
# Integrated simulation results

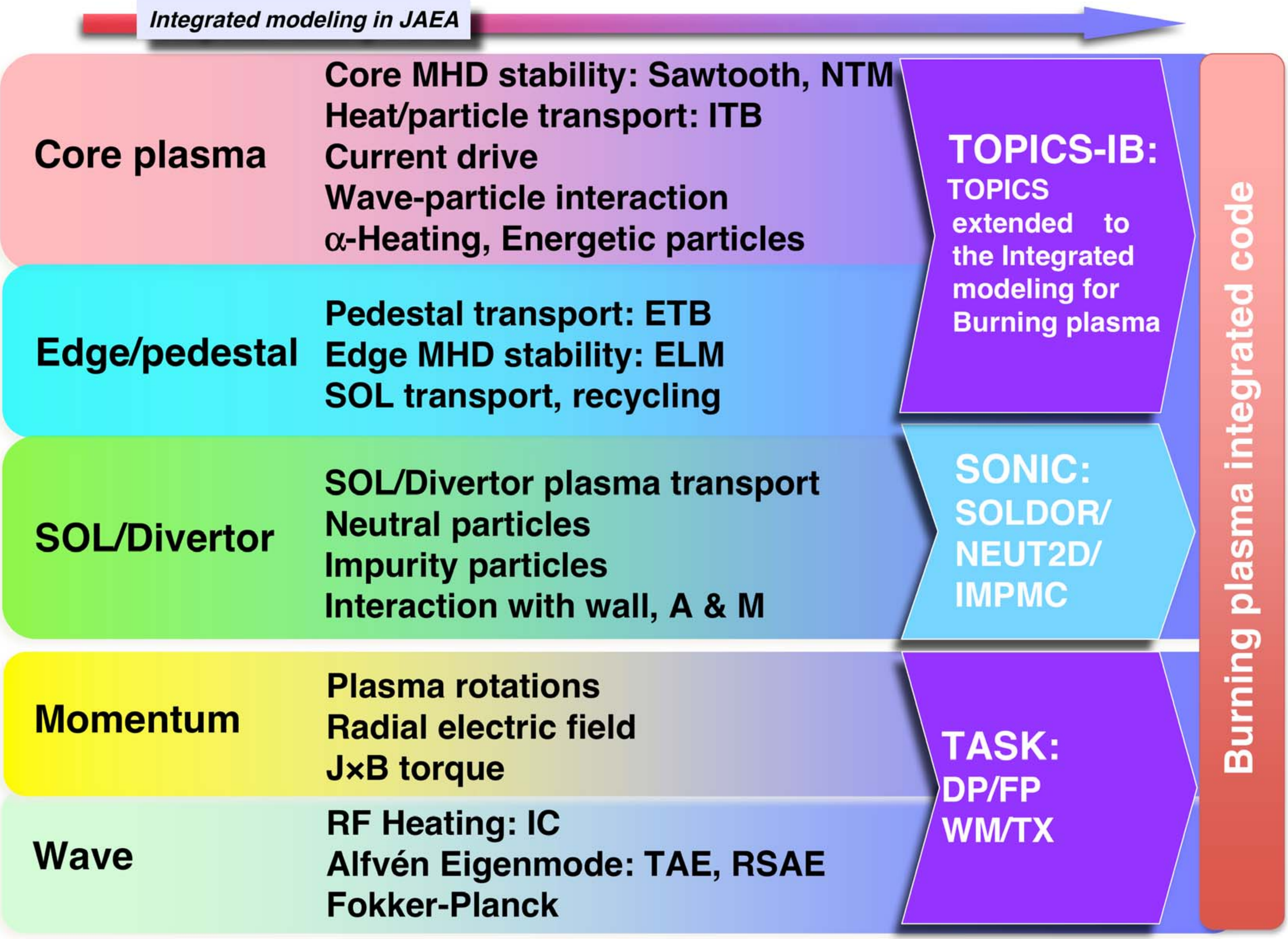
Critical gradient of α pressure











*Integrated modeling in JAEA*

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Heat/particle transport: ITB
Current drive
Wave-particle interaction
α-Heating, Energetic particles

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IMPMC

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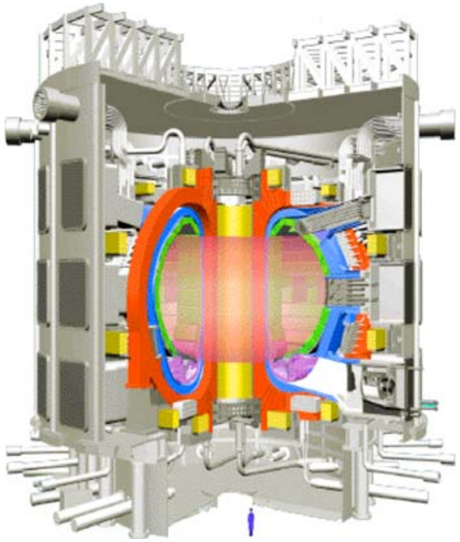
**Burning plasma integrated code**

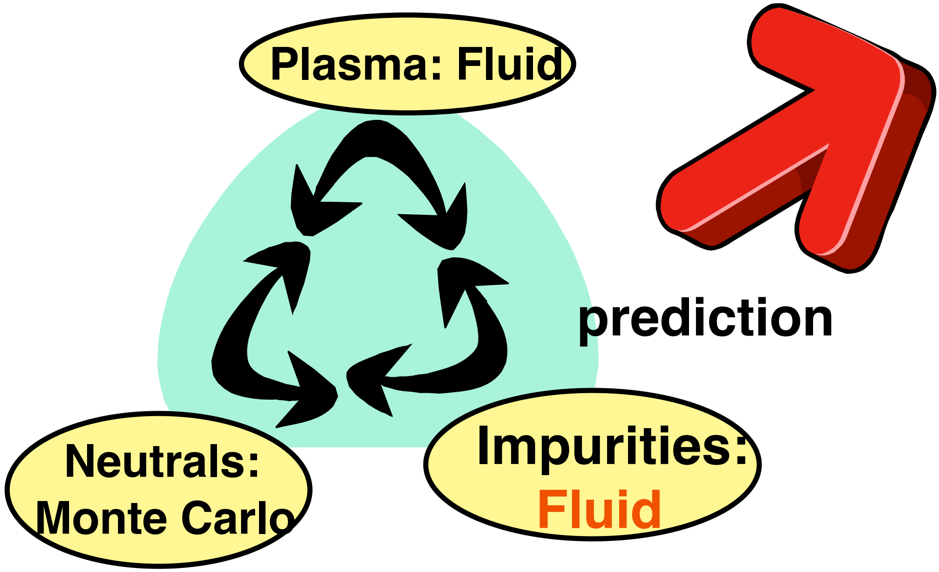
# Integrated Divertor Code for Fusion Reactor



**To investigate the power and particle control in tokamak reactor, integrated divertor codes have been developed.**

**The MC approach has an advantage to the flexibility of modelling.**

- Gyro-motion ==> Erosion
- Neutrals ==> Methane breakup
- Kinetic effect ==> Thermal force

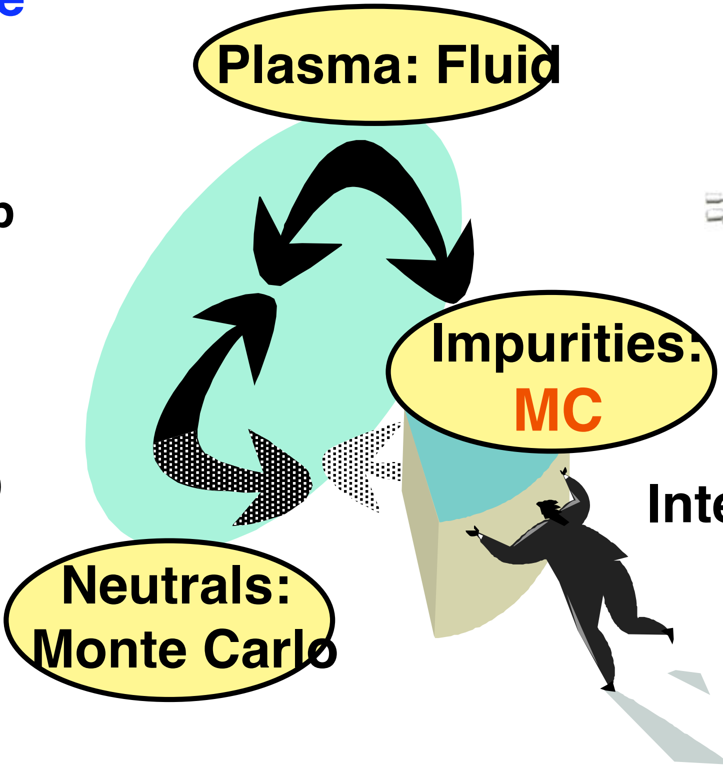


Plasma: Fluid

Neutrals: Monte Carlo

Impurities: Fluid

prediction



Plasma: Fluid

Impurities: MC

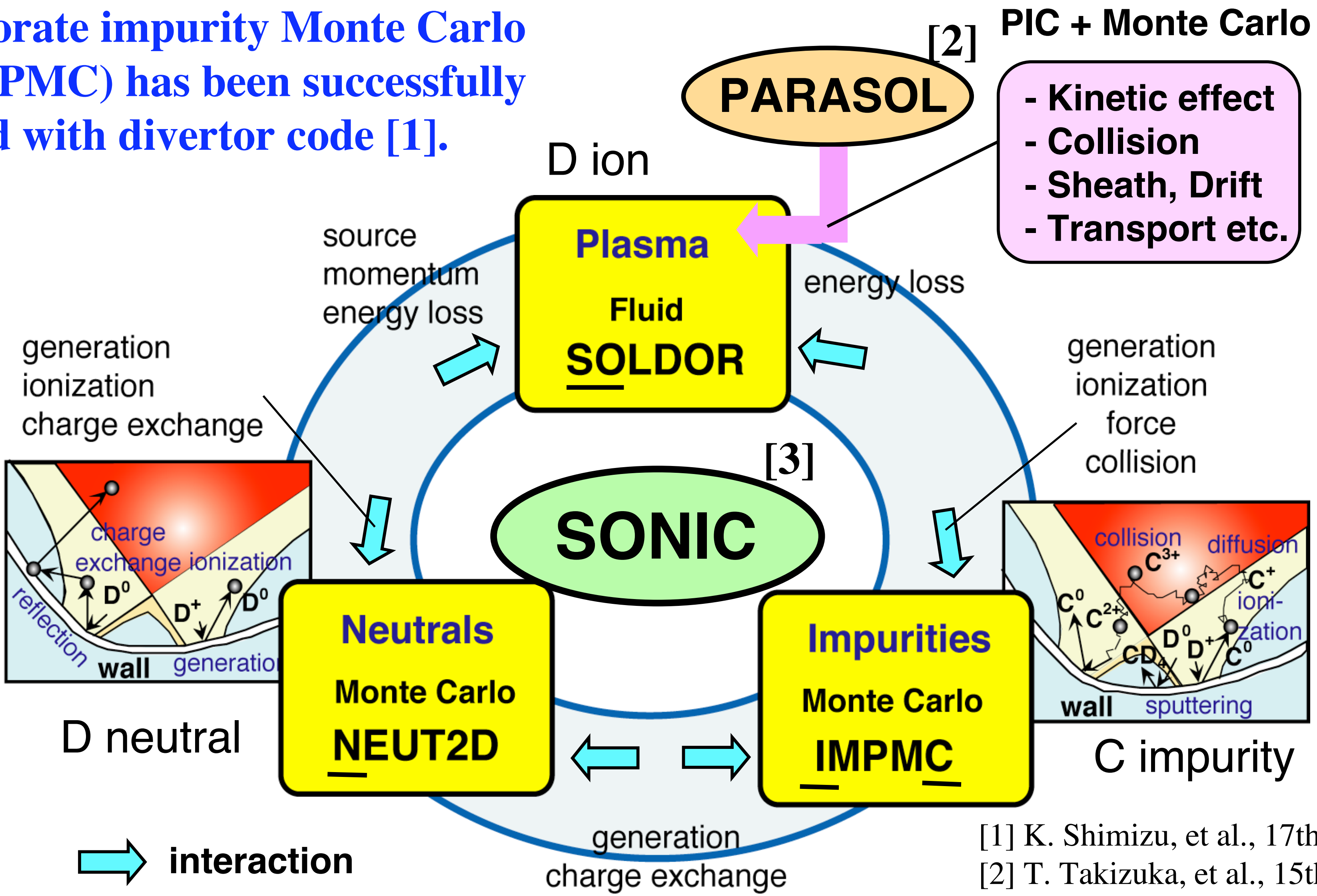
Neutrals: Monte Carlo

Interpretation

**But should solve MC problems, Long CPU, MC noise, Steady-state.**

# Integrated Divertor Code in JAEA

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



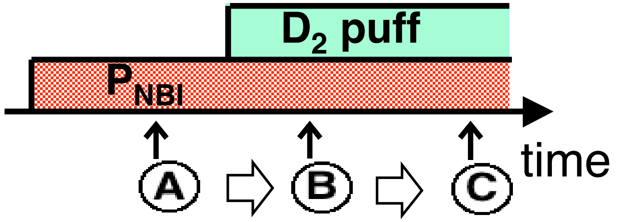
[1] K. Shimizu, et al., 17th PSI (2006).
[2] T. Takizuka, et al., 15th PSI (2002).
[3] H. Kawashima, et al., Plasma Fusion Res. **1** 031 (2006).

**IMPMC uses (1) Diffusion model using Langevin analytical solution to extend time step, (2) MPI with many particles to reduce MC noise, (3) Particle reduction scheme to obtain steady state.**

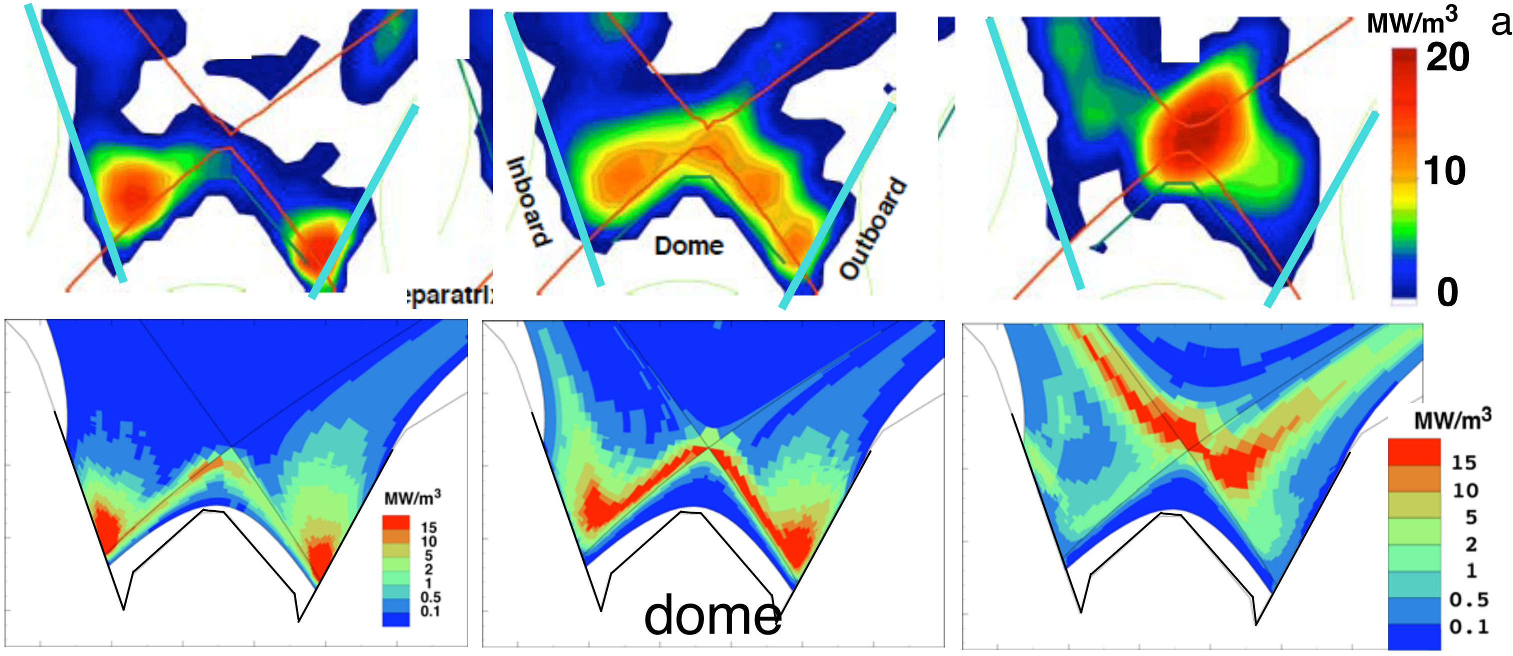
# Simulation of X-point MARFE with SONIC

**To reduce the high heat load onto the divertor plate, the control method for impurity retention in the divertor region should be established.**

SONIC simulations reproduced the formation of X-point MARFE in JT-60U discharge with high heating NBI



attached detached Xp MARFE



**JT-60U experiment**

(PNB=15~20MW)

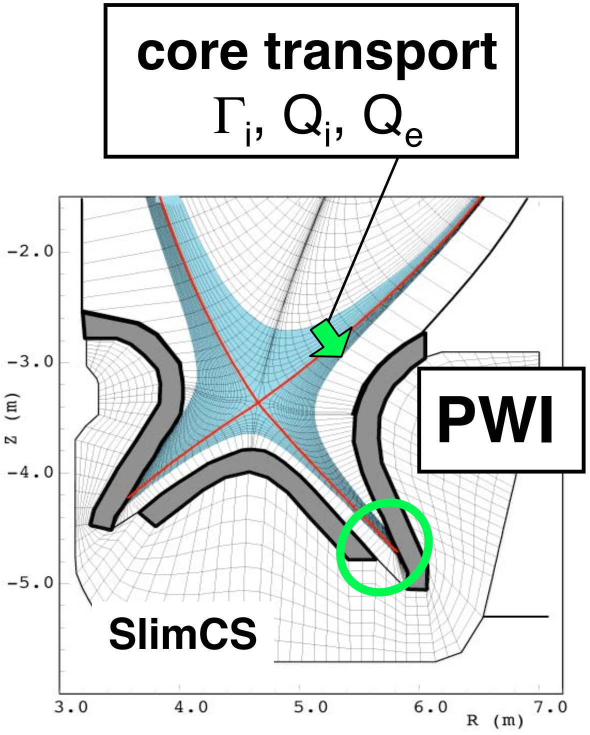
**SONIC simulation**

(PNB=15MW)

attached plasma detached plasma X-point MARFE

**Hydrocarbons sputtered from the dome contribute to the enhanced radiation near the X-point.**

# Plan of integration

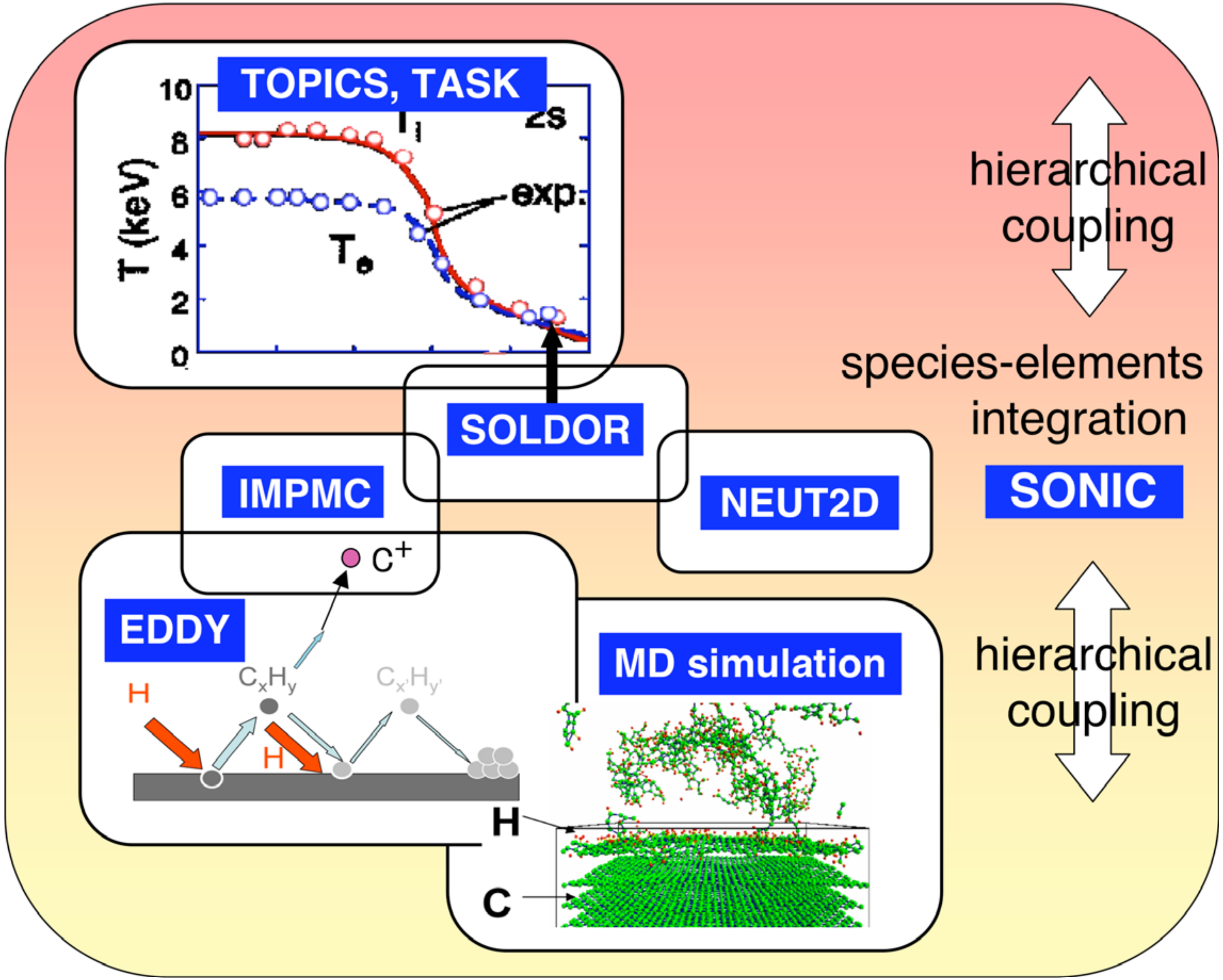


core transport
$\Gamma_i$, $Q_i$, $Q_e$

PWI

SlimCS

1. Coupling with core transport
2. Including plasma wall interactions



TOPICS, TASK

SOLDOR

IMPMC

NEUT2D

EDDY

MD simulation

SONIC

hierarchical coupling

species-elements integration

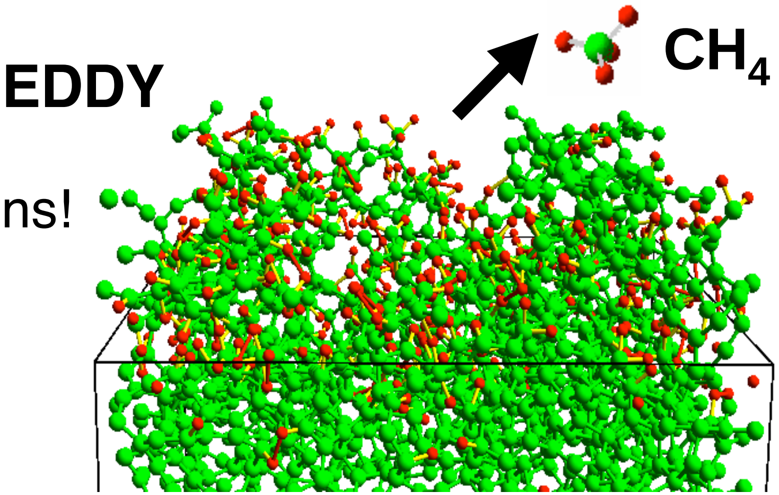
hierarchical coupling

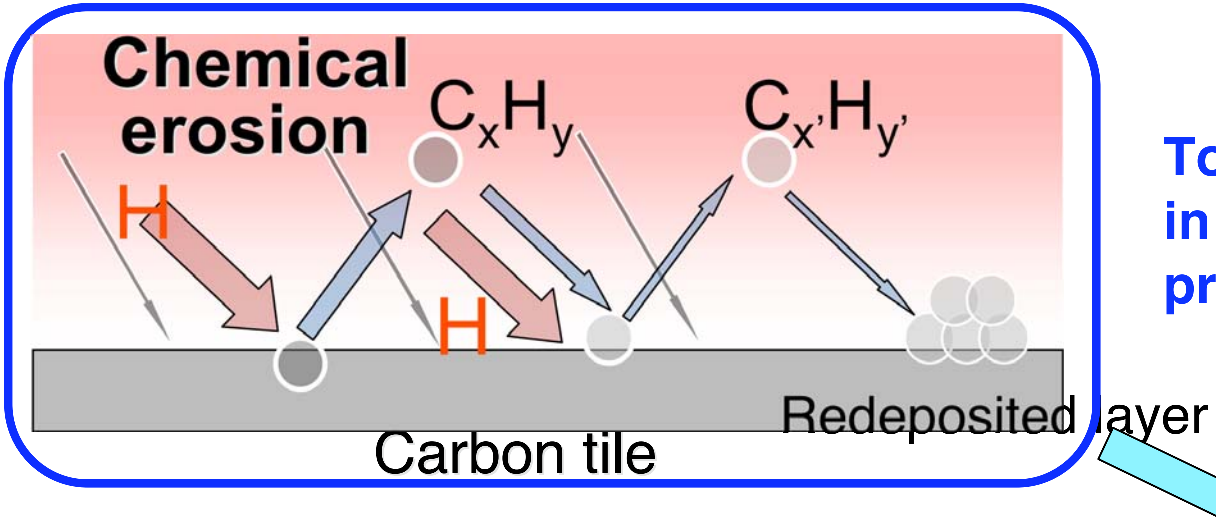
# EDDY/IMPMC Simulation

## for Methane Breakup Model

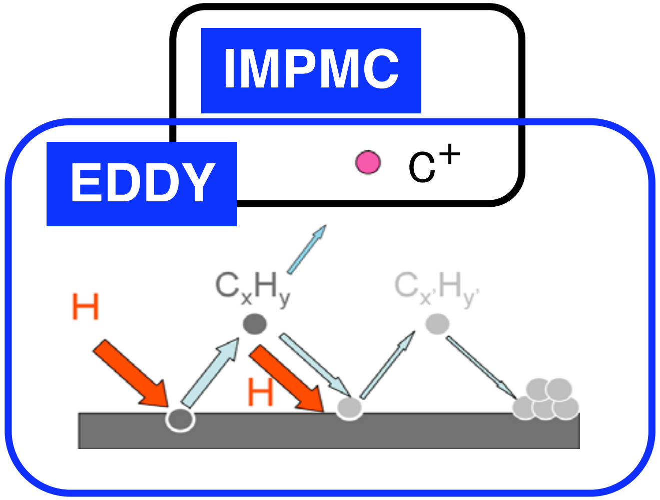
Plasma ion irradiation on material surfaces
Dynamic erosion and deposition processes
**Impurity transport in near-surface plasma**
dissociation processes of hydrocarbons: 700 reactions!

$C_xH_y$,x=1,2,3 (R.K.Janev, D.Reiter, Rep.FZ-Juelich, Jul-3966 (2002); Jul-4005 (2003))





**To investigate migration of carbon in large scale and contamination process into the main plasma,**

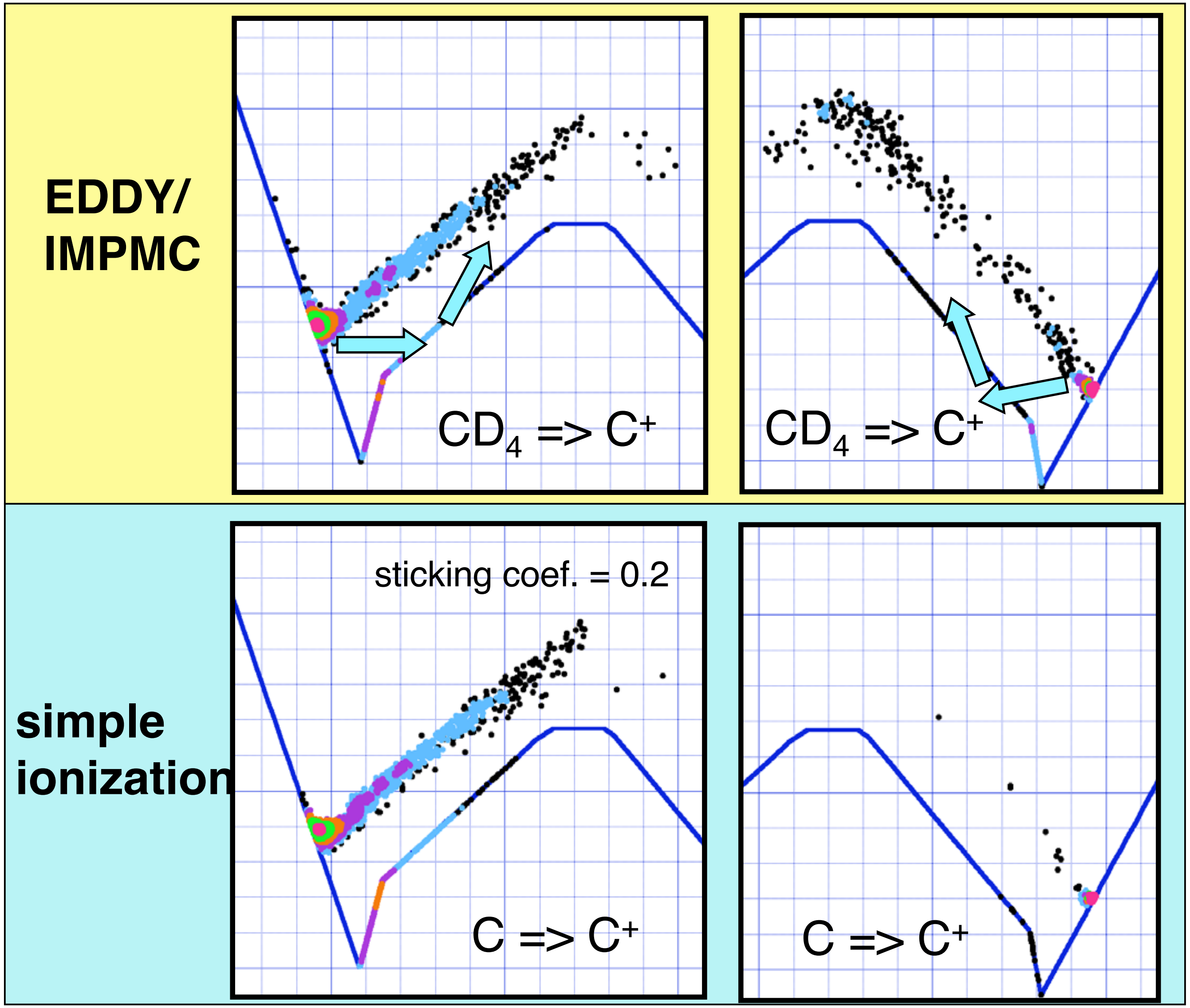


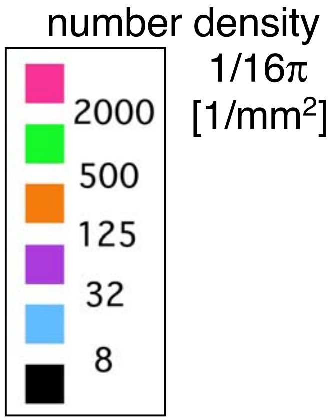
Comparison with the observed erosion distribution:
a small sticking of hydrocarbons and erosion yield of 0.01–0.02 on the outer divertor plate.

# Comparison with Simple Methane Breakup

**detached inner divertor**
**($n_{ed}$ = 4.2×$10^{20}$ $m^{-3}$, $T_{ed}$ = 1.7 eV)**

**attached outer divertor**
**($n_{ed}$ = 1.9×$10^{20}$ $m^{-3}$, $T_{ed}$ = 17 eV)**

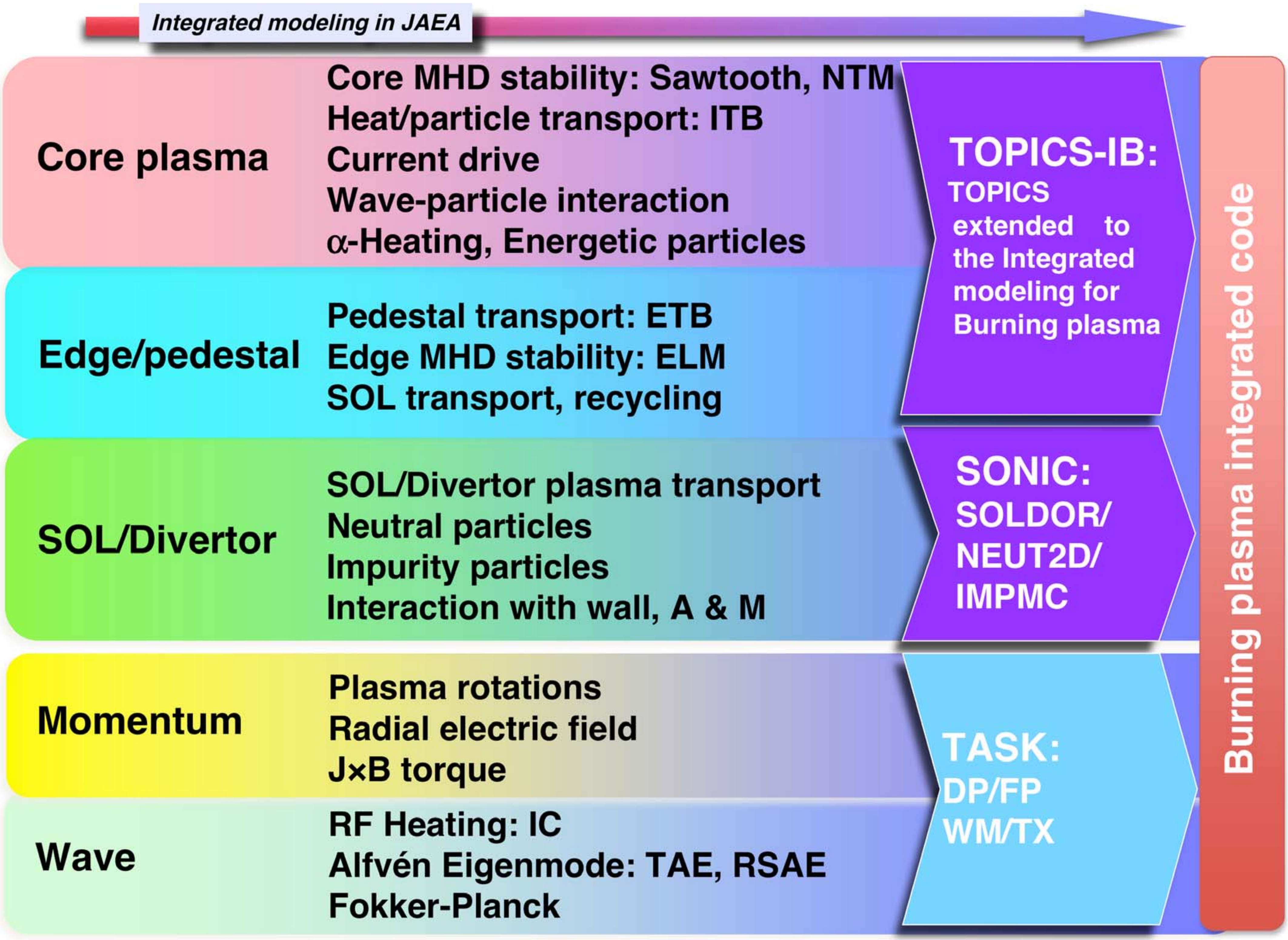




In detached plasma, simple model is relatively good approximation

In attached plasma, the methane breakup can not be simplified

The dome with a small sticking coefficient enhances the contam- ination of carbon into the main plasma.



*Integrated modeling in JAEA*

**Core plasma**

- Core MHD stability: Sawtooth, NTM
- Heat/particle transport: ITB
- Current drive
- Wave-particle interaction
- α-Heating, Energetic particles

**Edge/pedestal**

- Pedestal transport: ETB
- Edge MHD stability: ELM
- SOL transport, recycling

**SOL/Divertor**

- SOL/Divertor plasma transport
- Neutral particles
- Impurity particles
- Interaction with wall, A & M

**Momentum**

- Plasma rotations
- Radial electric field
- J×B torque

**Wave**

- RF Heating: IC
- Alfvén Eigenmode: TAE, RSAE
- Fokker-Planck

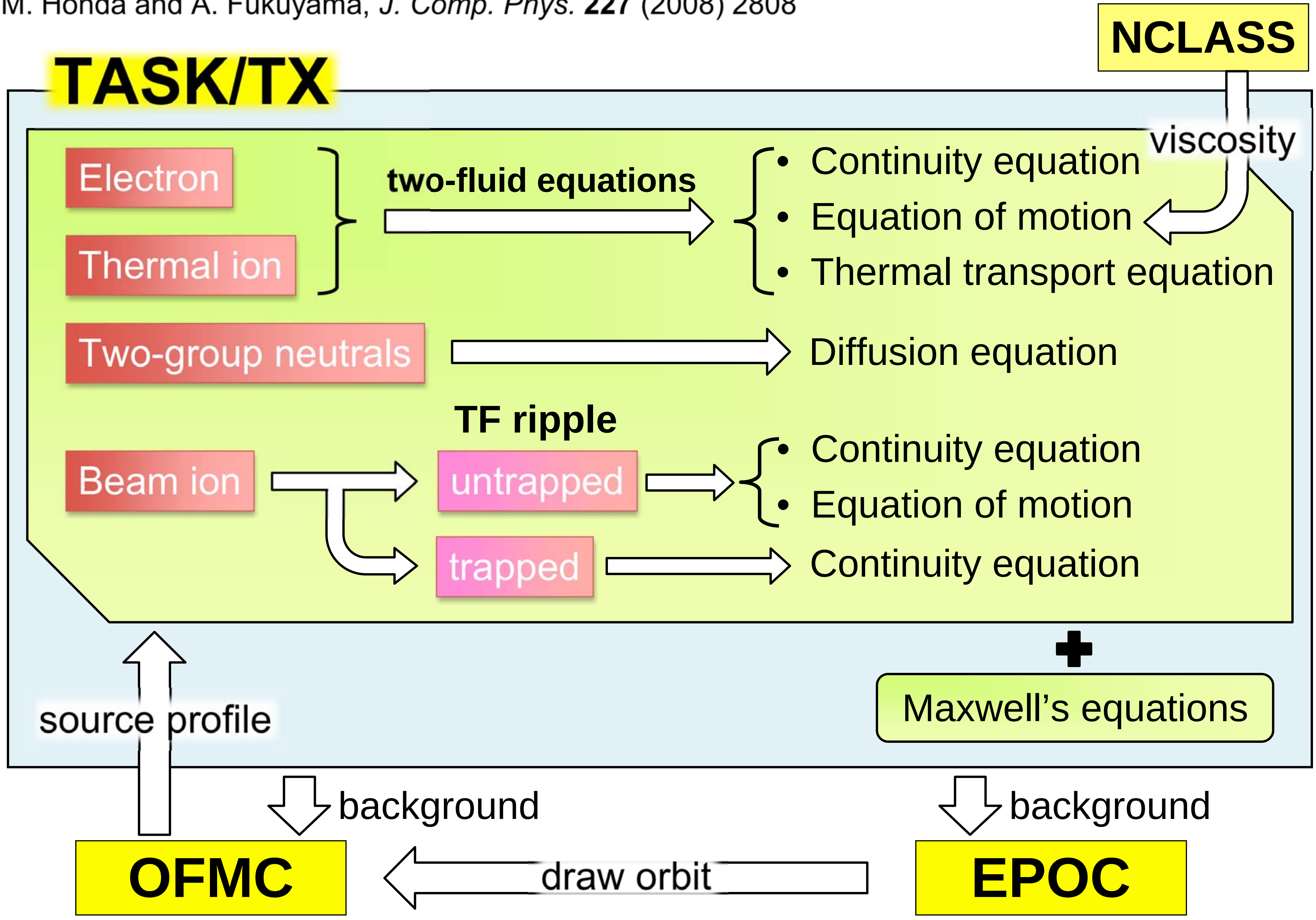
**TOPICS-IB:**
TOPICS extended to the Integrated modeling for Burning plasma

**SONIC:**
SOLDOR/
NEUT2D/
IMPMC

**TASK:**
DP/FP
WM/TX

Burning plasma integrated code

M. Honda and A. Fukuyama, *J. Comp. Phys.* **227** (2008) 2808



**NCLASS**

**TASK/TX**

viscosity

Electron

Thermal ion

**two-fluid equations**

- Continuity equation
- Equation of motion
- Thermal transport equation

Two-group neutrals

Diffusion equation

**TF ripple**

Beam ion

untrapped

- Continuity equation
- Equation of motion

trapped

Continuity equation

Maxwell's equations

source profile

background

background

**OFMC**

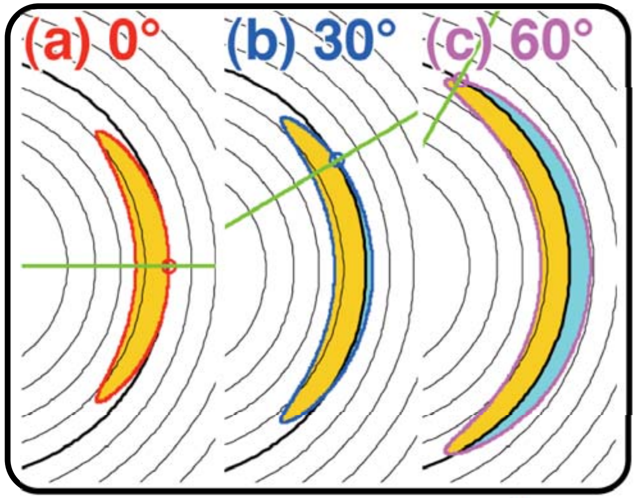
draw orbit

**EPOC**

# Toroidal rotation induced by charge separation

Motivation

1) Ionization of fast neutrals from NB produces electrons and fast ions.
2) Owing to the toroidal drift, the trapped ion especially deviates from the birth flux surface.
3) The charge separation continues as long as NB is injected, causing local charge imbalance.
4) A radial current flows in the bulk plasma to maintain quasi-neutrality.
5) A resultant *j*×*B* torque drives the toroidal rotation.

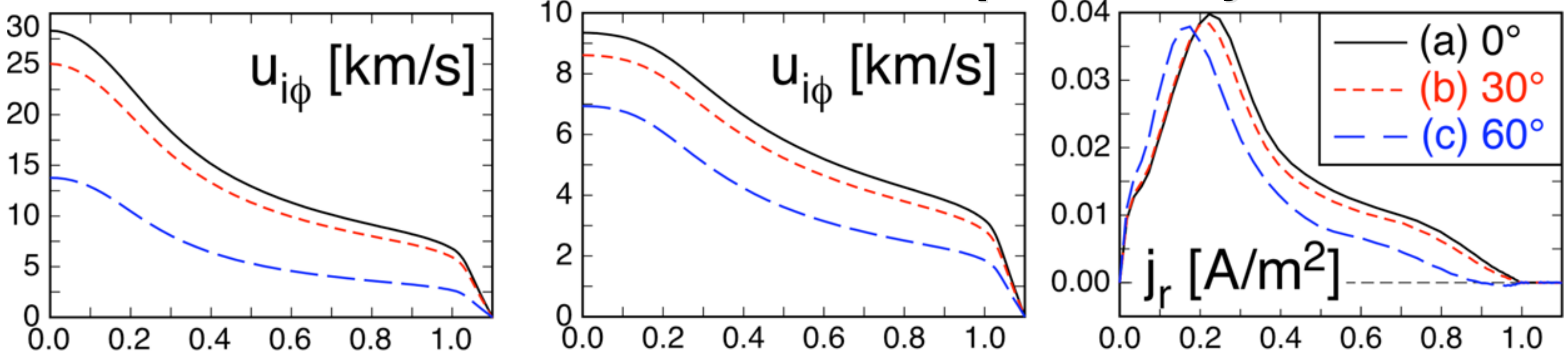


## TASK/TX simulations with OFMC

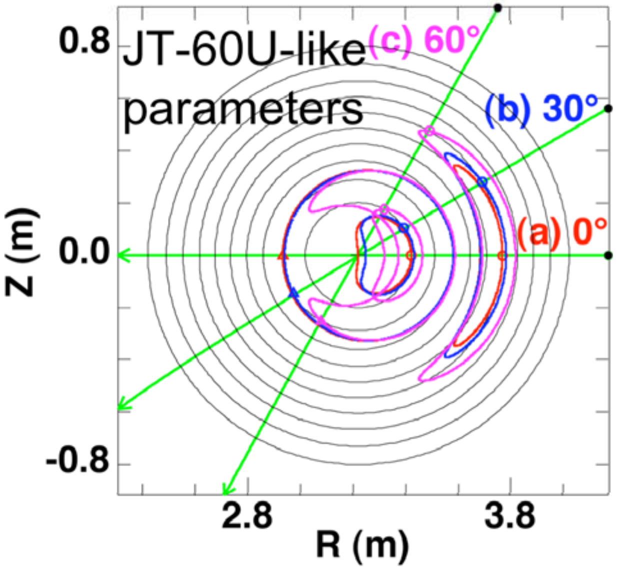
- have reproduced the toroidal rotation by charge separation due to near perpendicular NBI.
- have clarified that horizontally-injected NB (case (a)) drives the rotation most efficiently.

important → Banana width and magnetic field at birth position

### TASK/TX results with source profiles by OFMC



(1) w/ col. torque (2) w/o col. torque (3) $j_r$



M. Honda et al., *2008 Fusion Energy Conf.*, TH/P8-15

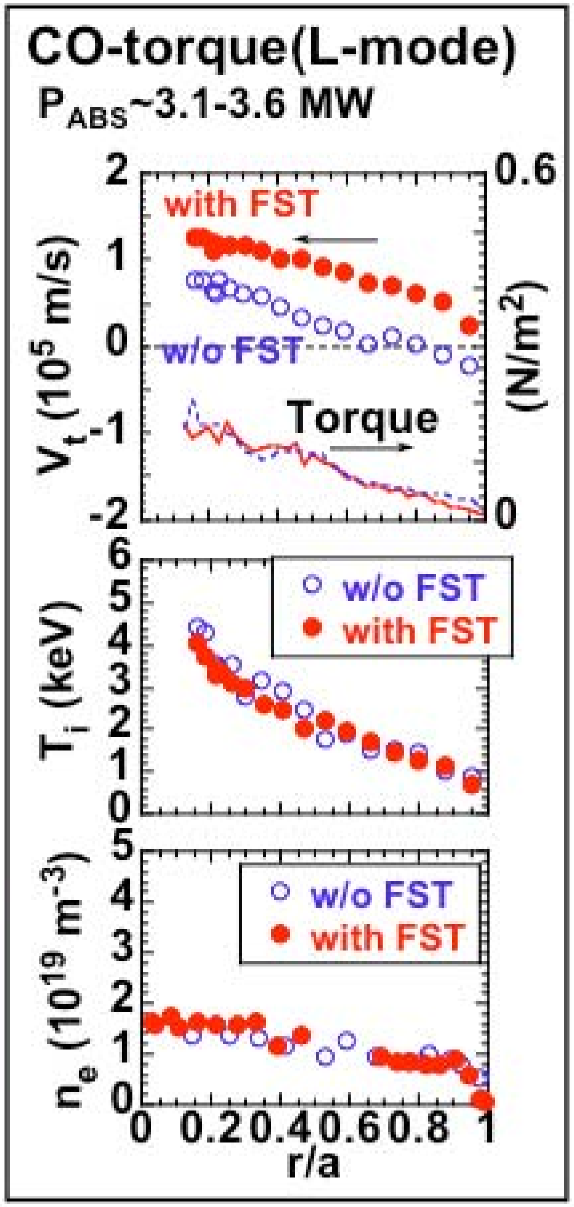
# Effect of ripple loss of fast ions on toroidal rotation in JT-60U

In JT-60U experiments, effects of ripple loss of fast ions on toroidal rotation have been extensively studied [5].

- Installation of ferritic steel tiles (FSTs) reduces the toroidal field ripple amplitude roughly in half.
- The discharge after installing FSTs (smaller ripple loss) was compared with the otherwise equivalent case with the ripple loss amplitude before installing FSTs.

Loss of fast ions due to the ripples drives the plasma rotation in the counter direction.

From the experimental analysis, the counter rotation rather than the pressure gradient has strong ties with the formation of the inward $E_r$.



[5] M. Yoshida, et al., PPCF **48** (2006) 1673

# Ripple loss channels

- In our model ripple transport is assumed to be governed by three different types of transport mechanisms.
  - Vertical drift (collisionless ripple-trapping) loss

    Beam ions trapped in ripple well drift vertically with grad *B* drift velocity $v_d$.

$$u_b^{rp} \approx \frac{\Delta r}{z / v_d} = \frac{z}{r} v_d = \frac{m_b v_b^2}{2 Z_b e B R} \frac{NqR\delta}{r}, \quad where\ \Delta r = \frac{z^2}{r}, z = NqR\delta$$

  - Collisional diffusive loss
    - High collisionality regime (ripple-plateau diffusion) [7]

$$D_{RP} \cong \nu_b \Delta r^2, \quad where\ \nu_b \cong \frac{\varepsilon^{1/2} v_b}{4\sqrt{2} K(\xi) qR} \cong \frac{\varepsilon^{1/2} v_b}{10.5 qR}, \ \Delta r^2 = \pi N \left( \frac{\varepsilon}{q} \right)^3 \delta^2 \rho^2$$

    - Low collisionality regime (ripple-resonance diffusion) [8]

$$D_{CB} \cong \frac{N^{9/4} q^{13/4} R \rho_b \delta^{3/2}}{\varepsilon^{5/2}} \nu_D$$

  - Collisionless stochastic diffusion [9]

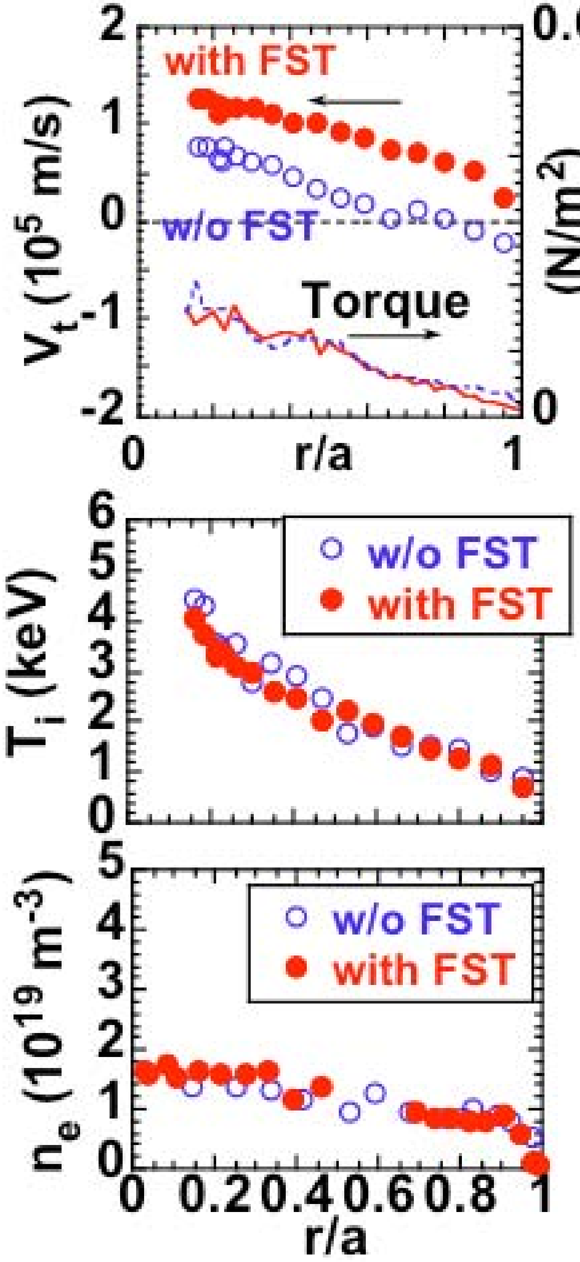
    Diffusion coefficient is the same as ripple-plateau diffusion coefficient, $D_{RP}$.

    Stochastic diffusion occurs where the following GWB criterion is satisfied.

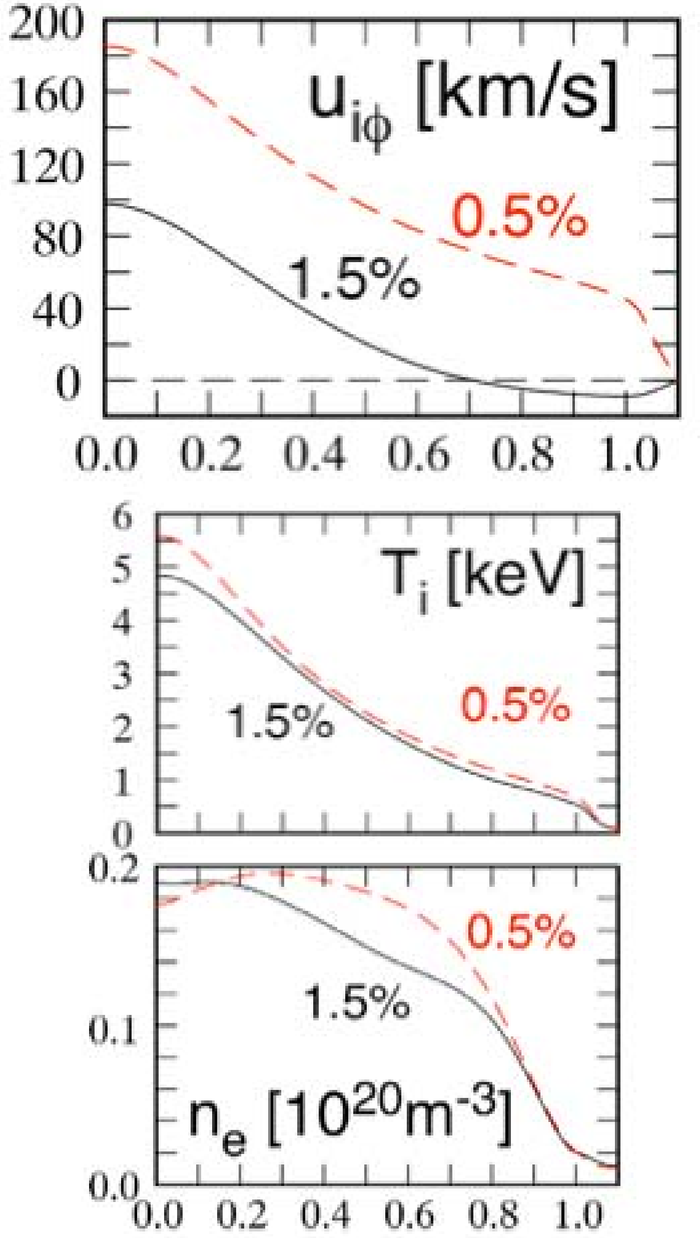
$$\delta_C \le \left[ \left( \frac{\pi N q}{\varepsilon} \right)^{3/2} \rho \frac{dq}{dr} \right]^{-1}$$

[7] A. H. Boozer, PoF **23** (1980) 2283
[8] V. Ya. Goloborod'ko et al., Physica Scripta **T16** (1987) 46
[9] R. J. Goldston et al., PRL **47** (1981) 647

## JT-60U Experiment



## TASK/TX Simulation



# Summary

## Core integrated code TOPICS-IB

- Core-SOL-div. integration for study of ELM loss & cycle
- Integration with 1d1v FP code for study of AE modes effect on $\alpha$ particle confinement

## Divertor integrated code SONIC

- IMPMC-EDDY integration for study of methane breakup effect on X-point MARFE

## Two-fluid core code TASK/TX

- TASK/TX -OFMC integration for study of toroidal rotation induced by charge separation of fast ions (due to ripple & perpendicular NBI).