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

- Integrated modeling of transport and MHD -

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Japan Atomic Energy Agency

US/Japan JIFT workshop on Integrated simulation of fusion plasmas

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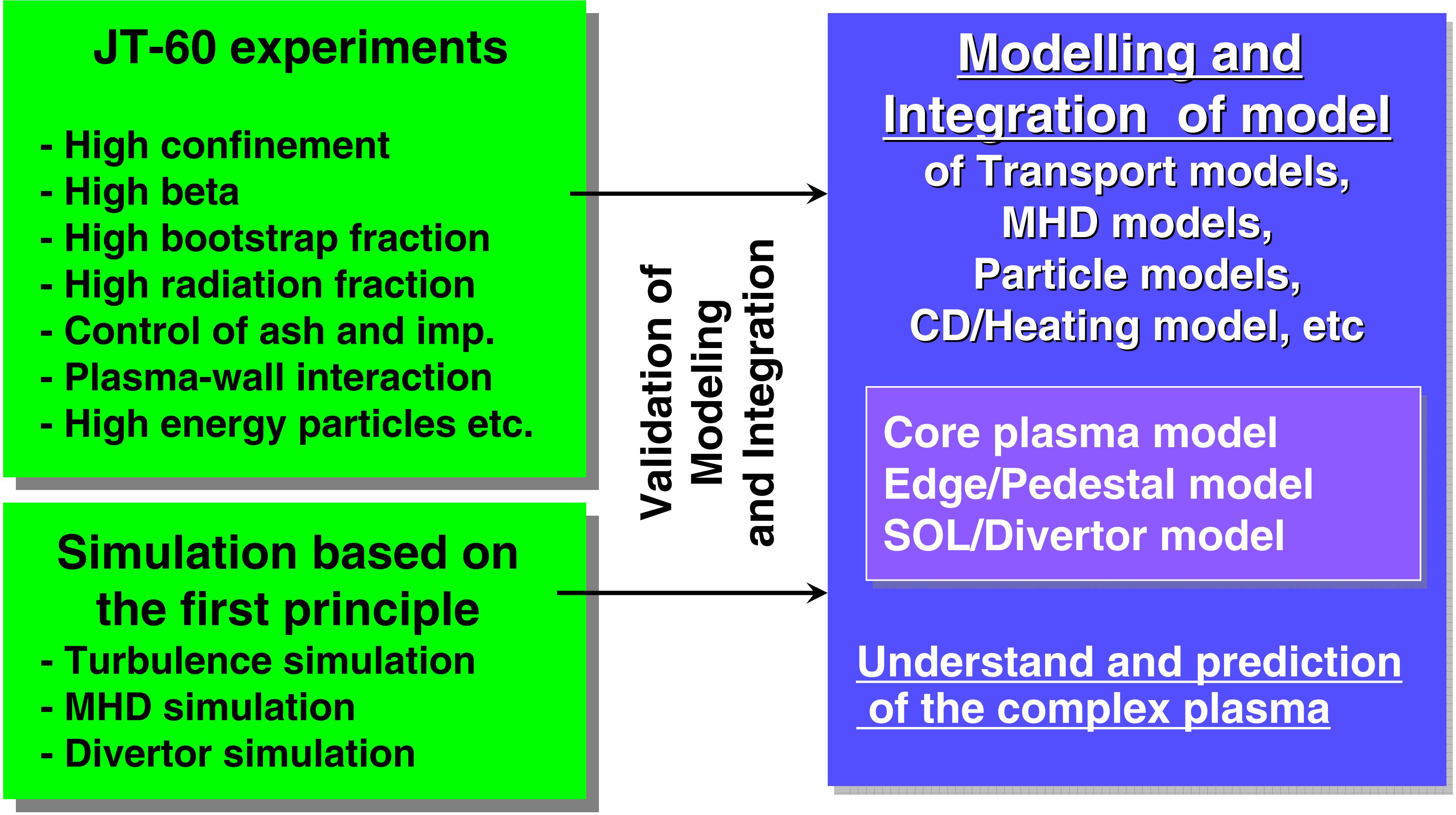
Strategy of Modelling / Integration of model

Purpose is to understand and control the burning plasma which has the complexity and autonomy. Modeling and integration of model are developed based on the fundamental researches.



JT-60 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

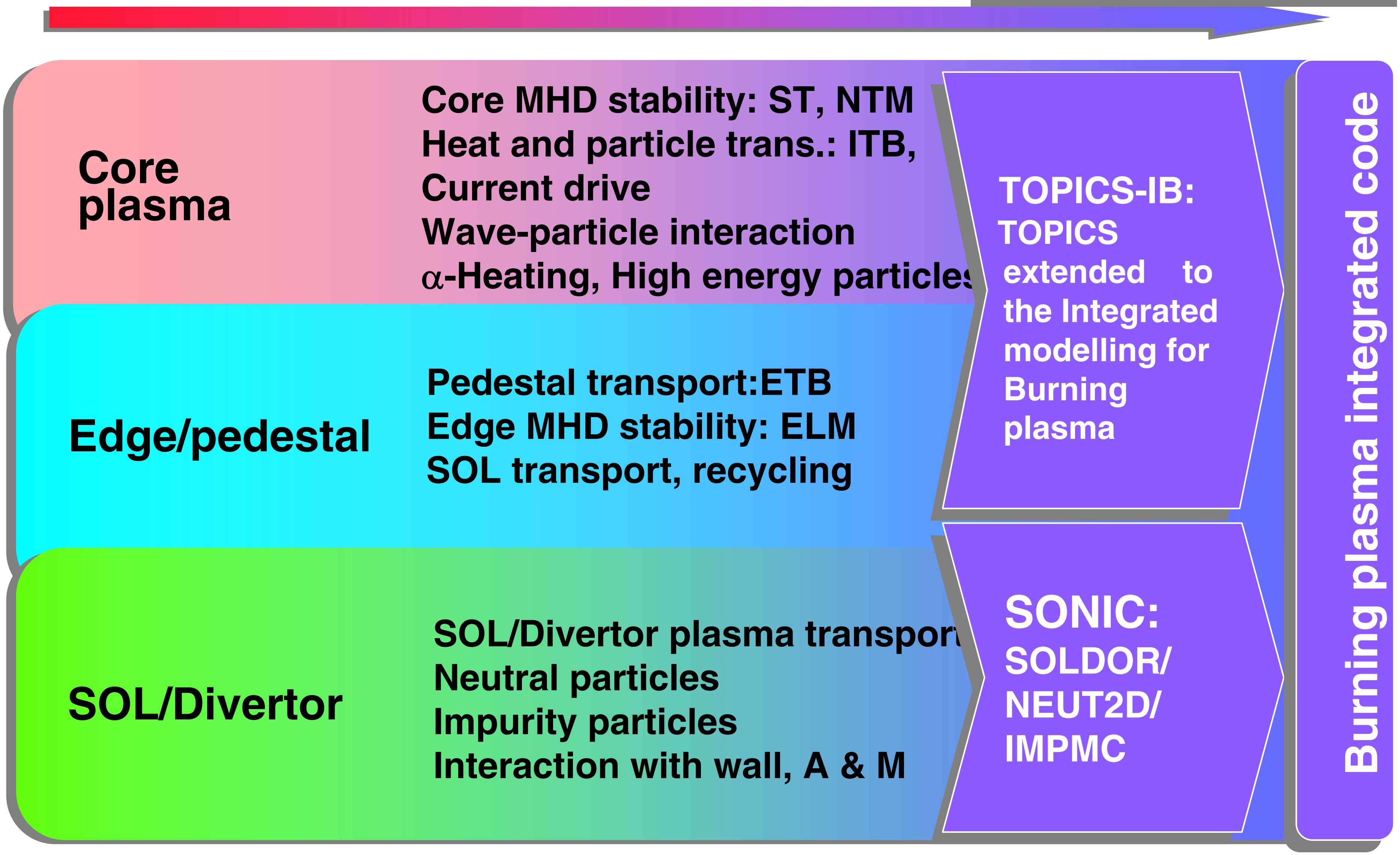
of Transport models,
MHD models,
Particle models,
CD/Heating model, etc

Core plasma model
Edge/Pedestal model
SOL/Divertor model

Understand and prediction of the complex plasma

Development of integrated models

Integrated modelling in JAEA



Core plasma

Core MHD stability: ST, NTM
Heat and particle trans.: ITB,
Current drive
Wave-particle interaction
α-Heating, High energy 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

TOPICS-IB:
TOPICS extended to the Integrated modelling for Burning plasma

SONIC:
SOLDOR/
NEUT2D/
IMPMC

Burning plasma integrated code

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

Transport code TOPICS

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

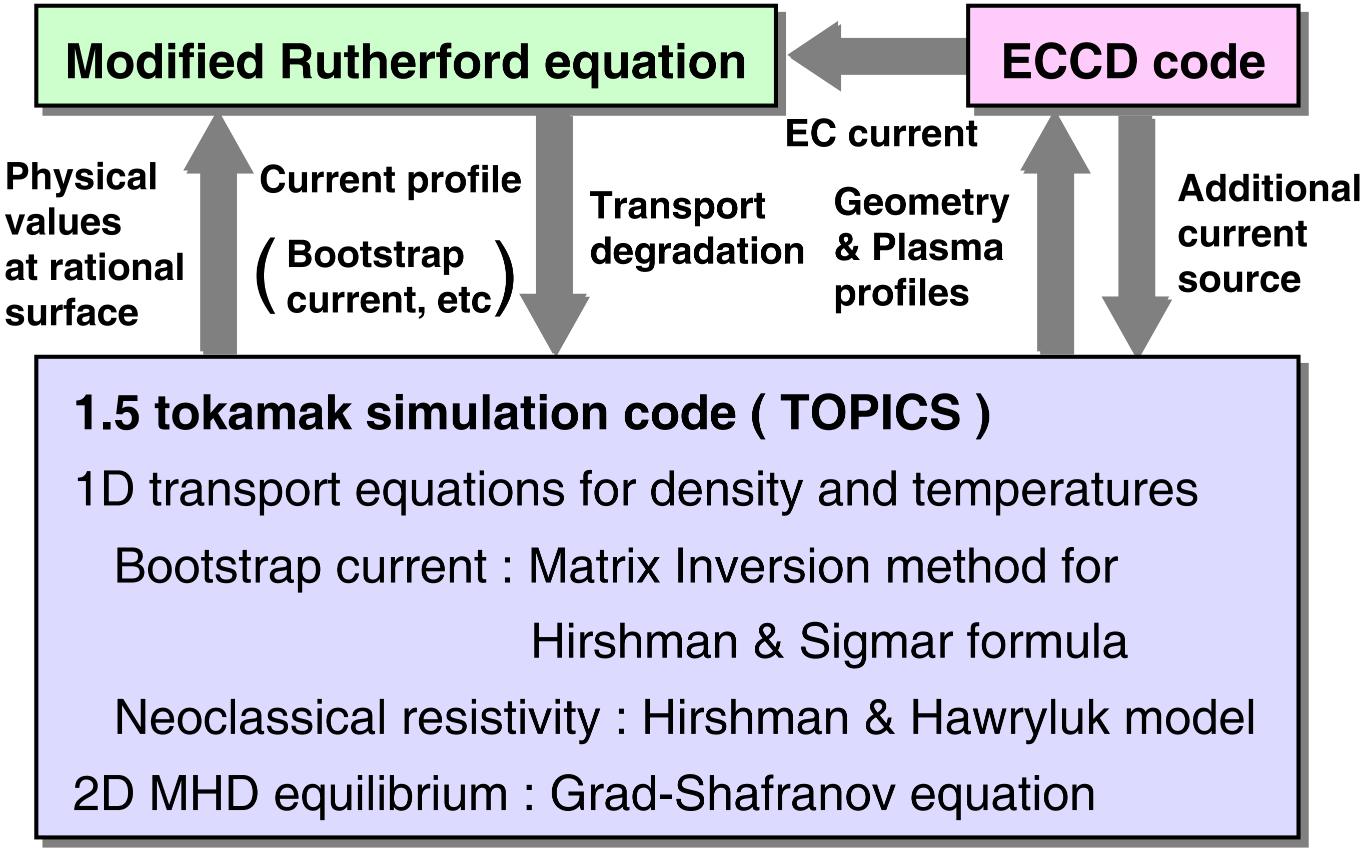
- **Transport**: Transport model in core plasma
- **Heating, Current Drive**: ECCD/ECH (Ray tracing, Relativistic F-P), NBCD(1 or 2D Fokker-Planck)
- **Neutral and α particles**: Orbit following monte carlo, F-P, Stix
- **Impurity Transport**: 1D transport for each impurities, Radiation: IMPACT
- **MHD**: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

Integrated NTM model

mainly with A.Isayama, N.Hayashi

NTM simulation by Integrated model

- □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.



1.5 tokamak simulation code (TOPICS)

1D transport equations for density and temperatures

Bootstrap current : Matrix Inversion method for Hirshman & Sigmar formula

Neoclassical resistivity : Hirshman & Hawryluk model

2D MHD equilibrium : Grad-Shafranov equation

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

NTM model: Modified Rutherford equation

$$\frac{\mu_0 a^2}{\eta}\frac{dW}{dt} = \Gamma_{\Delta'} + \Gamma_{BS} + \Gamma_{GGJ} + \Gamma_{pol} + \Gamma_{ECCD}$$

$\Gamma_{\Delta'}$: Classical tearing stability index term

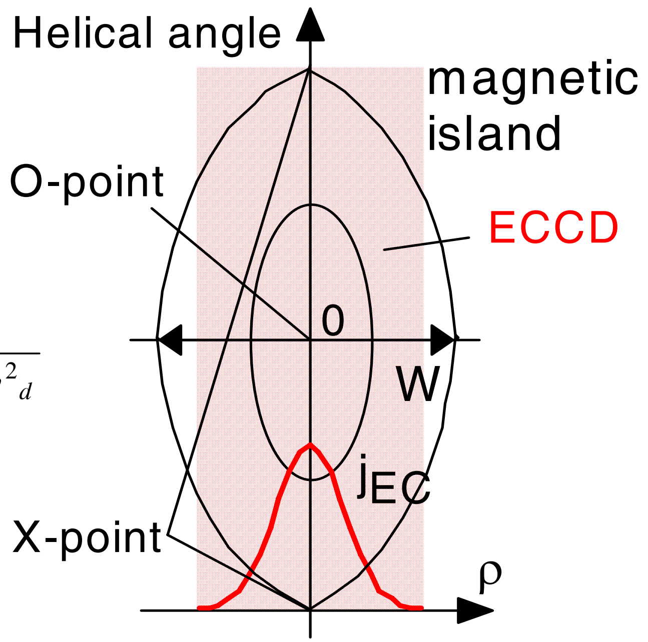
Γ_{BS} : Destabilization by the lack of the bootstrap current due to plasma profiles flattened in the magnetic island.

Γ_{GGJ} : Stabilization by magnetic well (Glasser-Green-Johnson effect)

$$\Gamma_{BS} = k_3 \mu_0 L_q j_{BS} \left\langle \left|\nabla\rho\right| / B_p \right\rangle \frac{w}{w^2 + w^2{}_d}$$

Γ_{pol} : Stabilization or destabilization by ion polarization current

Γ_{ECCD} : Stabilization by EC current compensating bootstrap current lost in the magnetic island.



χ : Diffusivities Di, χ_e, χ_i

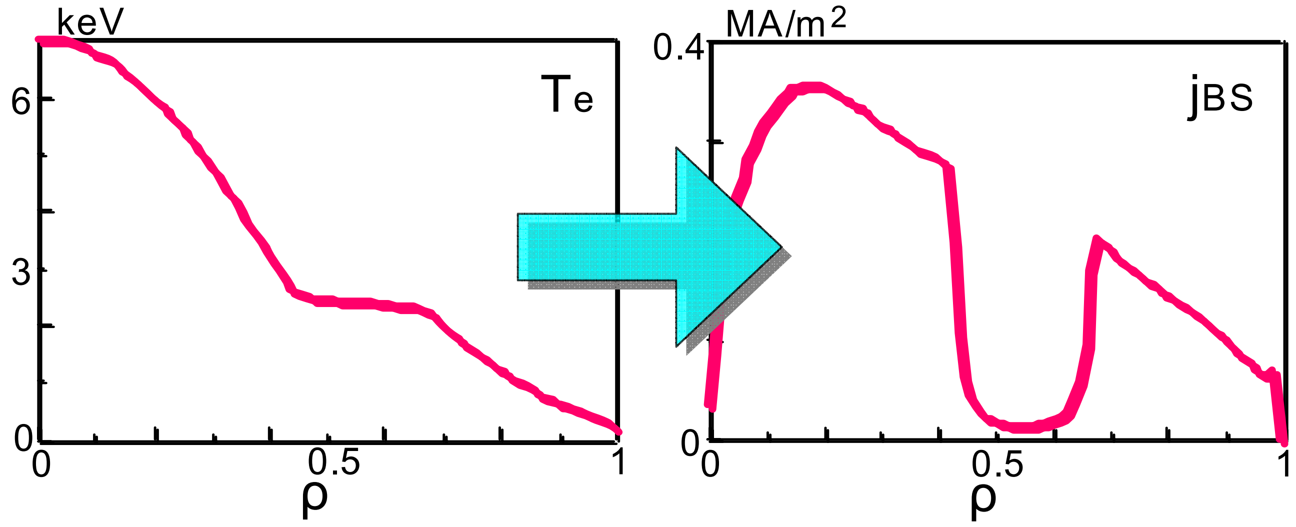
Degradation model in TOPICS

Flattening effect model:
Amplified diffusivities is enlarged inside island

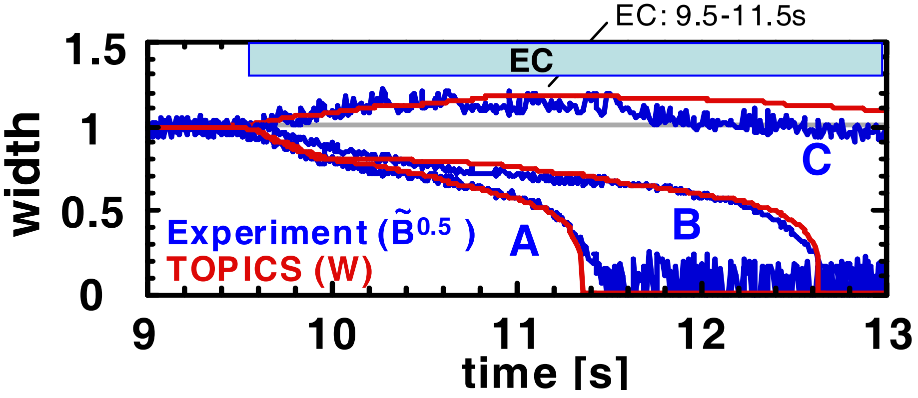
χ in island (ρ) = C(ρ) • χ(ρ)

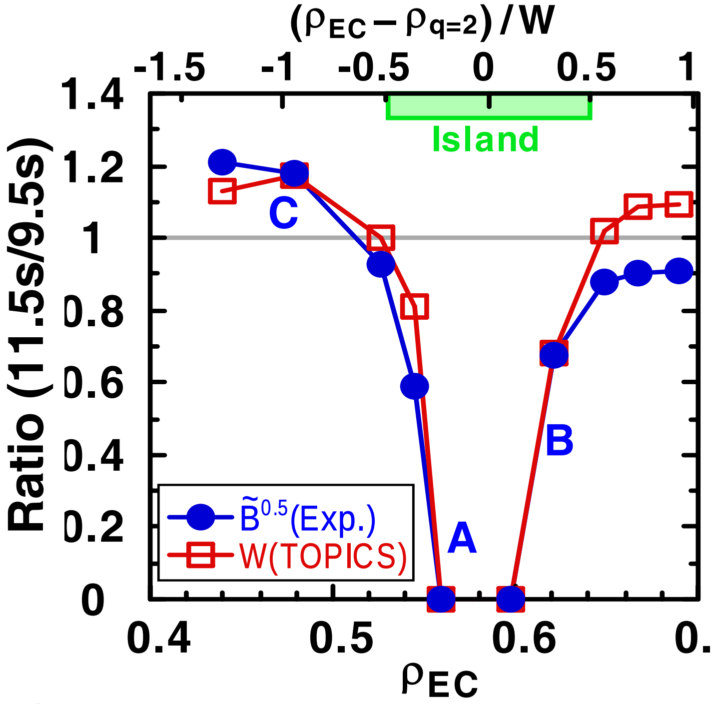
$$C(\rho) = 1 + C_0 \left\{ 1 - \left(\frac{\rho - \rho_s}{W/2} \right)^2 \right\}^2$$

$$C_0 = Min\left[20, \quad 10^4 \left(W - W_{init} \right)^3 \right]$$

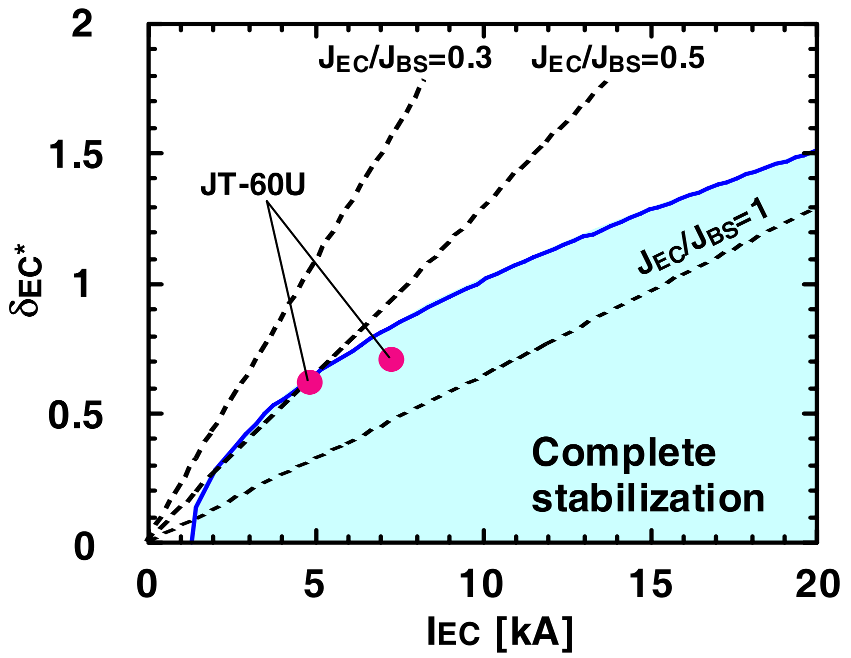


NTM simulation with modified Rutherford equation was verified by experimental results.





- 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]

Ideal MHD stability model

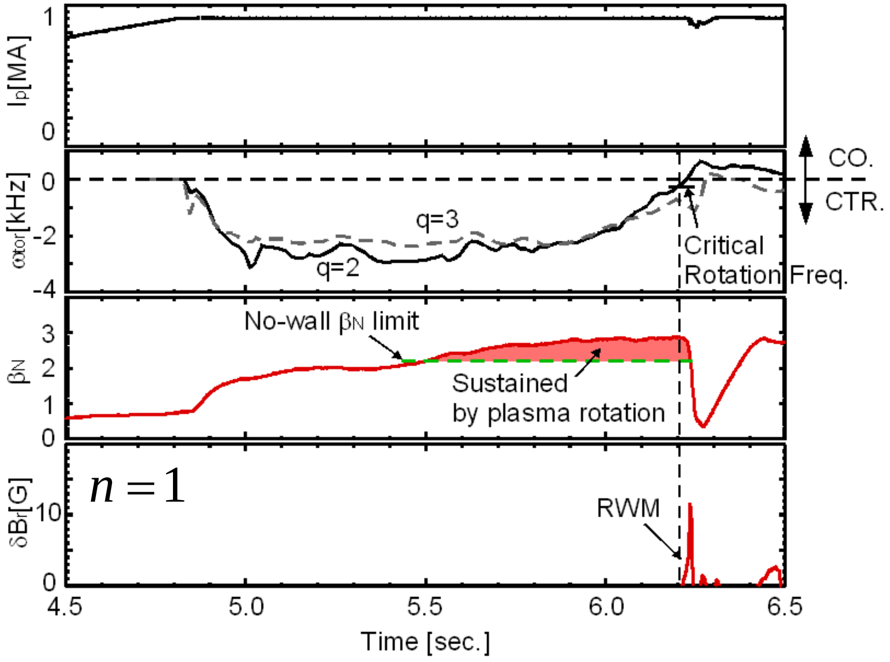
mainly with N.Aiba, S.Tokuda

collaboration with
M. S. Chu[1)]**, P. B. Snyder**[1)]**, and H. R. Wilson**[2)]
1) General Atomics, 2) Univ. York

Background

In tokamaks, ideal MHD modes often limit plasma performance.

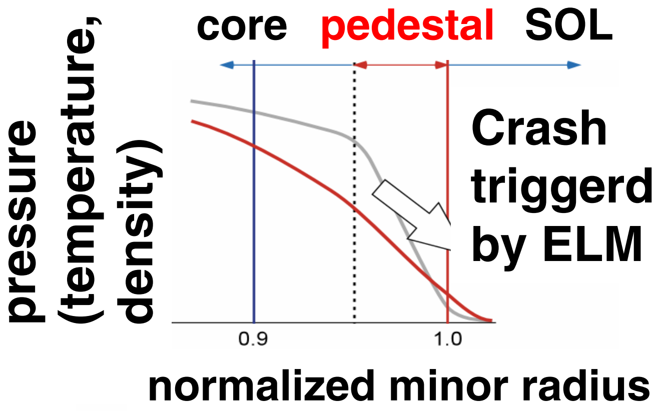
Kink-Ballooning Mode (Beta limits, related to RWM)

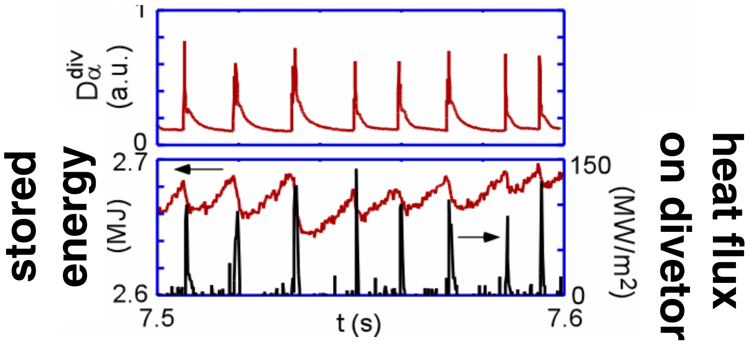


G.Matsunaga in this meeting 01aA03P.

Triggered by a global (low-*n*) MHD mode.

Edge Localized Mode (ELM) (Peeling-Ballooning Mode)





ELM experimental results in JT-60U

Triggered by an edge localized (intermediate to high-*n*) MHD mode.

Ideal MHD stability codes

MHD spectrum codes have been developed for the linear stability analysis of ideal MHD modes.

1. **For the low-*n* mode stability analysis**
   … ERATO[1], DCON[2], MISHKA[3] etc.
2. **For the intermediate to high-*n* mode stability analysis**
   … ELITE[4,5], MISHKA etc.

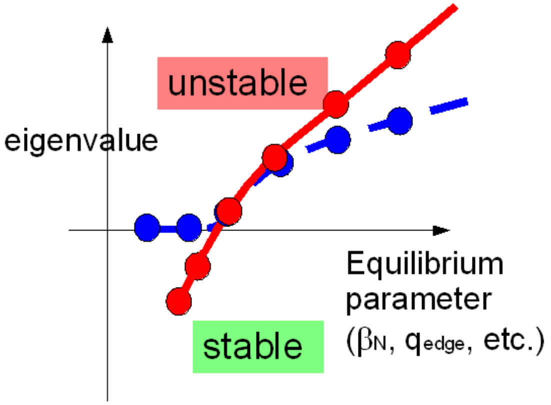
These codes have succeeded to analyze the stability of these MHD modes and are used for experimental analyses.

In JAEA, the MHD spectrum code MARG2D has been developed for a fast stability analysis of wide *n* range of ideal MHD modes[6,7].

[1] R. Gruber et al, Comput. Phys. Commun 21, 323 (1981).
[2] A.H.Glasser et al. in Bull. Am. Phys. Soc. vol.42, 1848 (1997).
[3] A.B.Mikhailovskii et. Al., Plasma Phys. Rep. 23, 844 (1997).
[4] H.R.Wilson et. al., Phys. Plasmas 9, 1277 (2002).
[5] P. B. Snyder et al., Phys. Plasmas 9, 2037 (2002).
[6] S Tokuda et al, J. Plasma Fusion Res. 73, 1141 (1997).
[7] N. Aiba et al., Comput. Phys. Commun. 175, 269 (2006).

Overview of the MARG2D code

With conventional ideal MHD model, the stability boundary of ideal MHD modes cannot be revealed explicitly in tokamaks.



MARG2D can identify explicitly the stability boundary of ideal MHD modes by solving the eigenvalue problem associated with the 2-D Newcomb equation with FEM[5].

$$N\mathbf{Y} = -\lambda R\mathbf{Y}\ , \quad (\mathbf{Y} = r\xi_r)$$

$$R_{l,m} \propto \begin{cases} (m/q-n)^2 & \ldots l = m \\ 0 & \ldots l \neq m \end{cases}$$

N **: Newcomb operator**

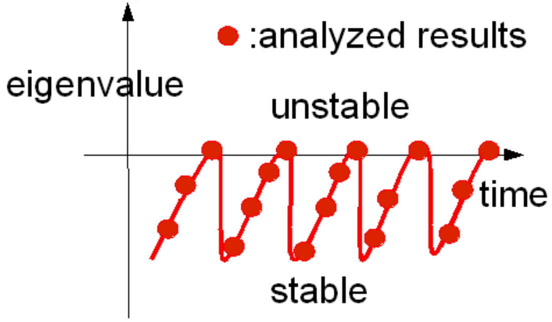
ξ_r: displacement in the *r* direction

m : poloidal mode number

n : toroidal mode number

q : safety factor

This is a fruitful advantage for the integrated simulation code: TOPICS-IB.



Computing the growth rate by adopting the plasma inertia

In the physical model introduced, since the physical inertia term is changed artificially, the linear growth rate γ of unstable ideal MHD mode cannot be estimated.

↓

Turn back the plasma inertia and the boundary condition at the rational surfaces after identifying the plasma is unstable.

$$R\mathbf{Y} \Rightarrow \rho(\mathbf{Y} + (\mathbf{V} - \beta\mathbf{Y}))$$

$$\lambda \Rightarrow \gamma$$

$\mathbf{V}$: displacement vector in the $\nabla\psi \times \mathbf{B}$ direction

ρ : plasma density

β : unorthogonality of the coordinate

This realizes to estimate γ with the incompressible assumption.

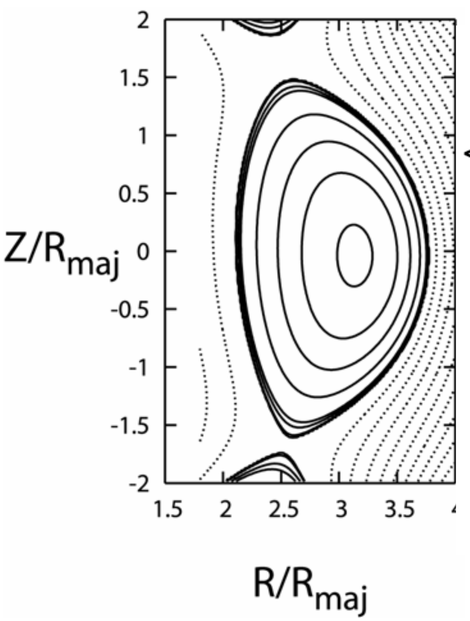
Benchmarking results between the MARG2D code and

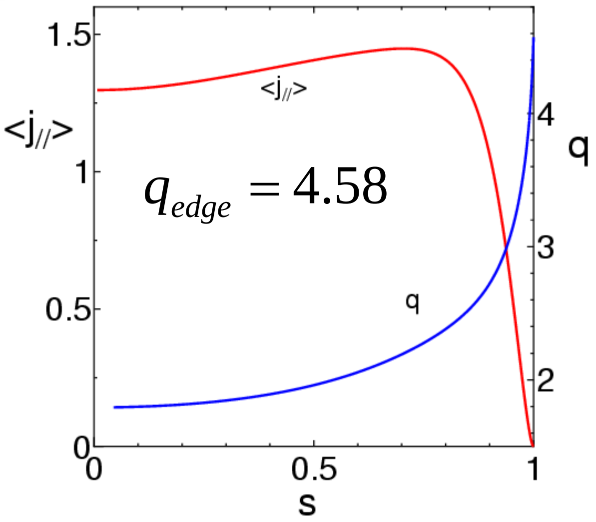
1. **the DCON code** by low-*n* external
   MHD modes stability analysis.
   (collaborated with Dr. M. S. Chu)

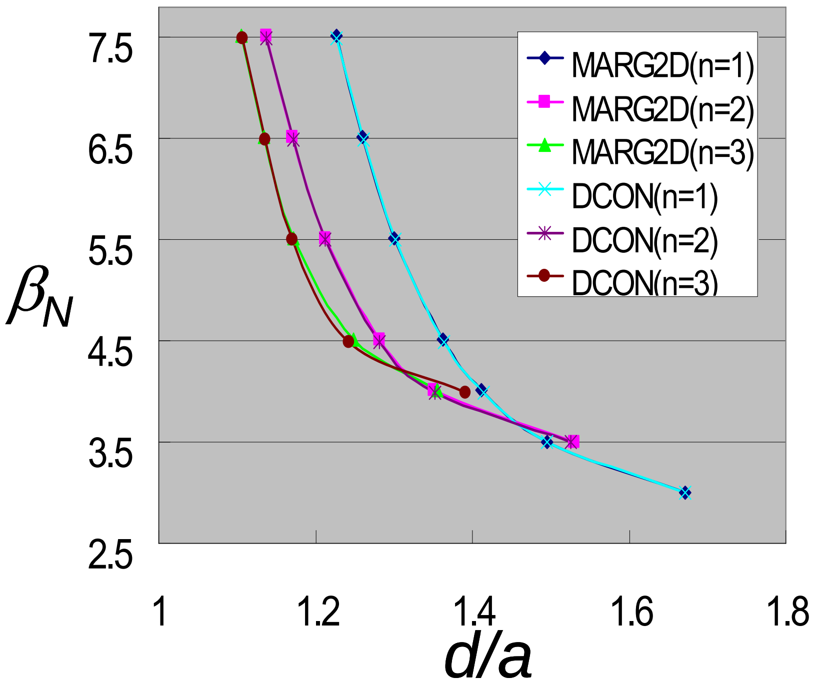
2. **the ELITE code** by intermediate
   to high-*n* external modes stability analysis.
   (collaborated with Dr. P. B. Snyder
   and Dr. H. R. Wilson)

Benchmarking results 1 (low-*n* mode case)

- **DCON solves the 2-D Newcomb equation with the shooting method[2].**
- **The wall position (*d/a*) dependence of the β_N limit determined by the external kink-ballooning mode stability as the benchmark test.**
  (The shape of the outermost surface and q_{edge} are fixed.)







Both codes shows the almost the same β_N limit determined by the MHD stabilities whose n=1, 2, and 3.

Benchmarking result 2
(intermediate to high-*n* mode case)

Integrated modelling in JAEA

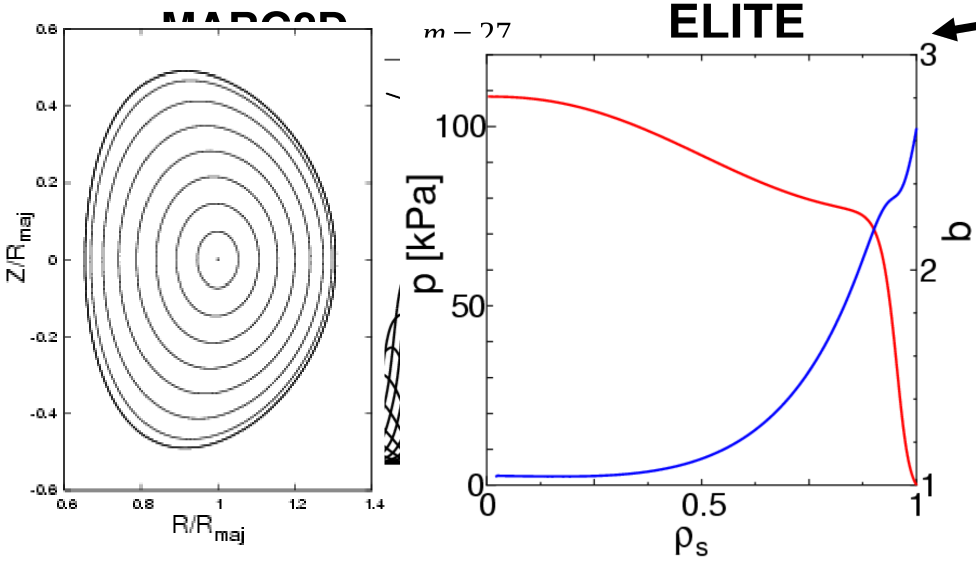
ELITE code solves the eigenvalue problem associated with the ideal MHD equation simplified with the high-*n* ordering (keep multiple orders for the intermediate and high-n mode analysis)[4,5].

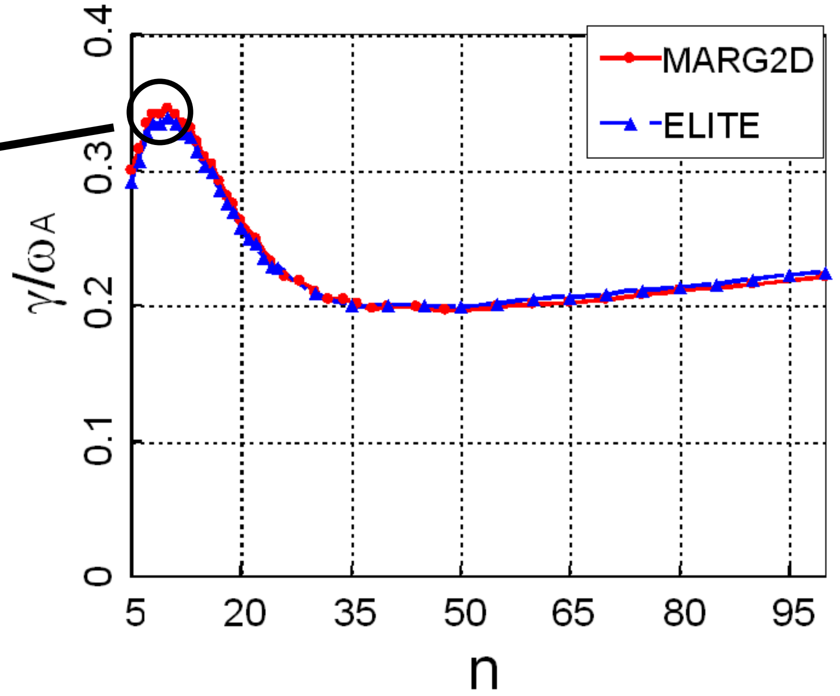
MHD stability whose n is from 5 to 100 is analyzed with MARG2D and ELITE.

Eigenfunction of the most unstable mode (n=10).

MARG2D

ELITE



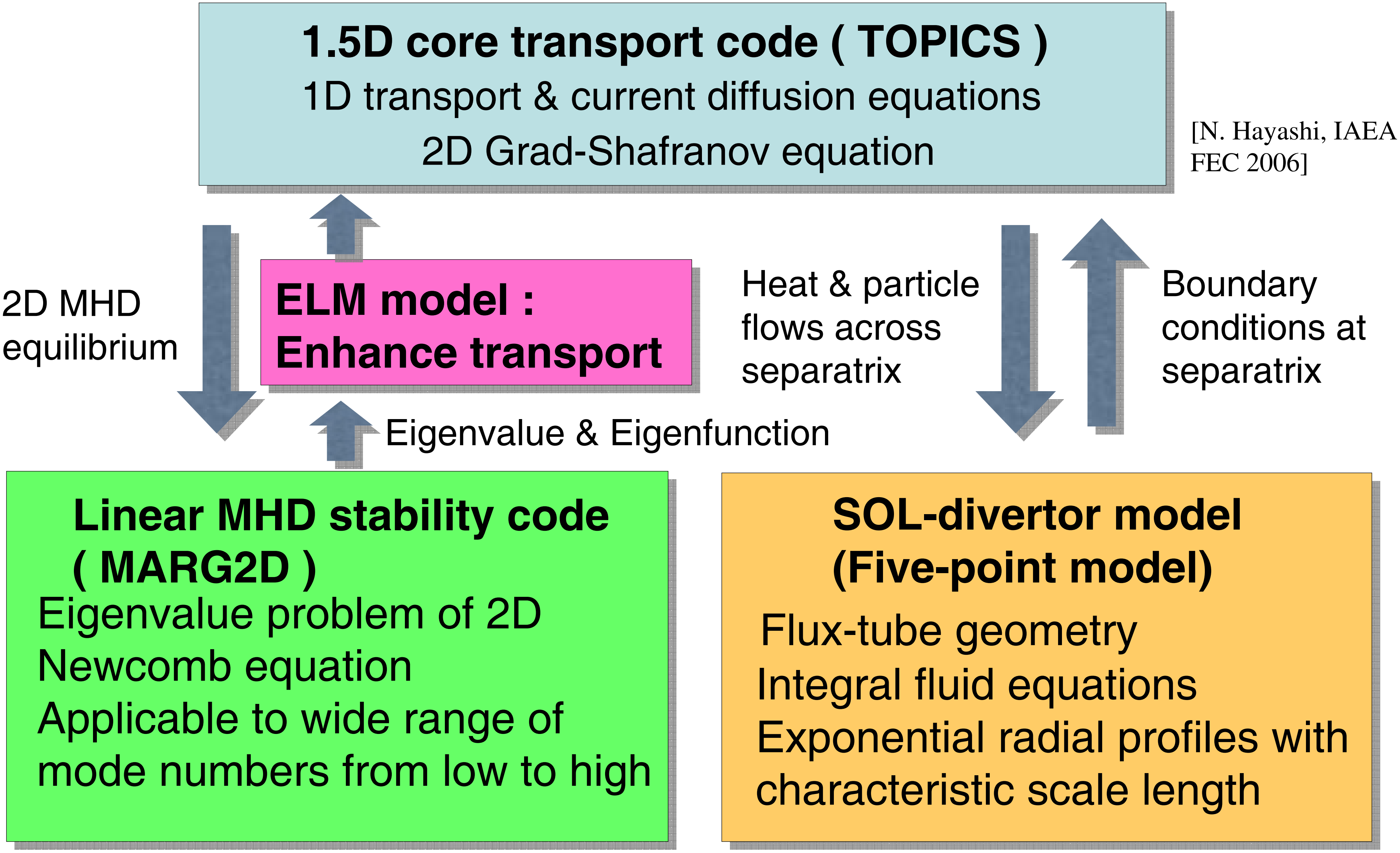


- **In the range 5≦n≦100, the growth rates (γ/ω_A) obtained by ELITE and MARG2D are well identical to each other.**
- **The structure of the eigenfunction is also almost same as each other.**

Integrated ELM model

mainly with N.Hayashi, T.Takizuka, N.Aiba

Integrated edge-pedestal model



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

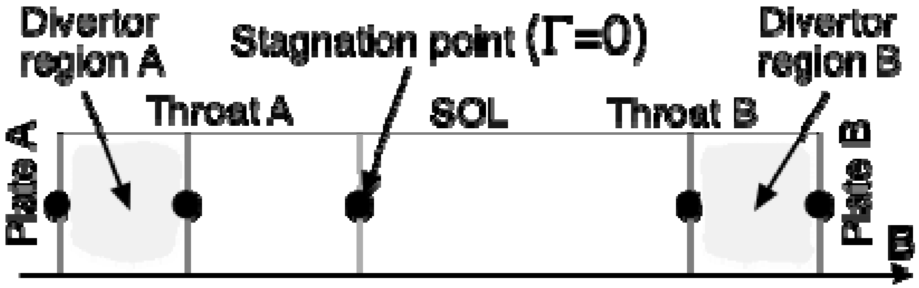
SOL model (Hayashi, PSI06)

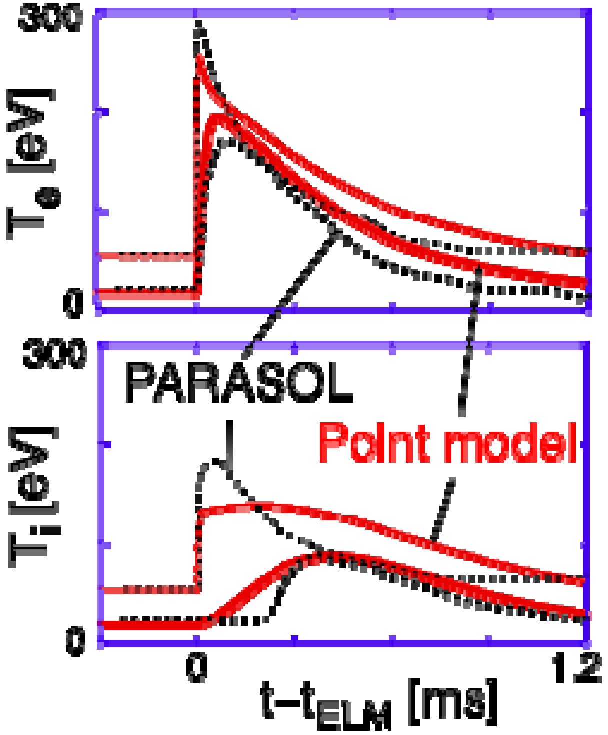
Point model based on integral fluid equations easily reproduces many static features found in experiments. (Stangeby, textbook)

Dynamic version of the point model (Five-point model) has been developed for the integrated ELM modeling.

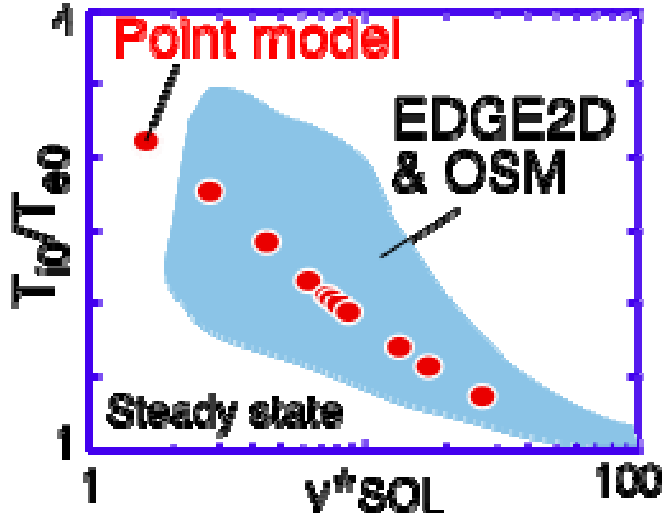
Flux-tube geometry

- **2 SOL & 2 divertor regions(5 positions)**
- **Symmetry assumed in this paper**





Validated by particle code



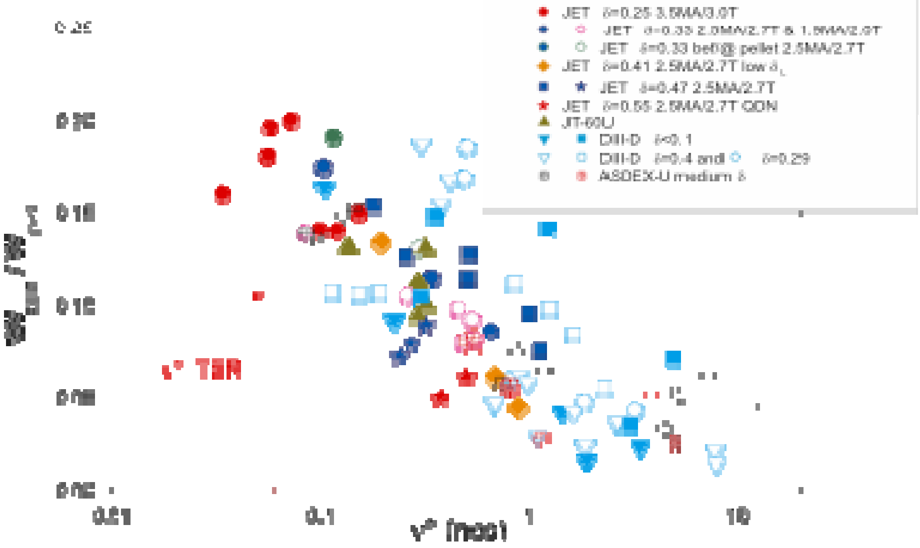
Validated by fluid codes

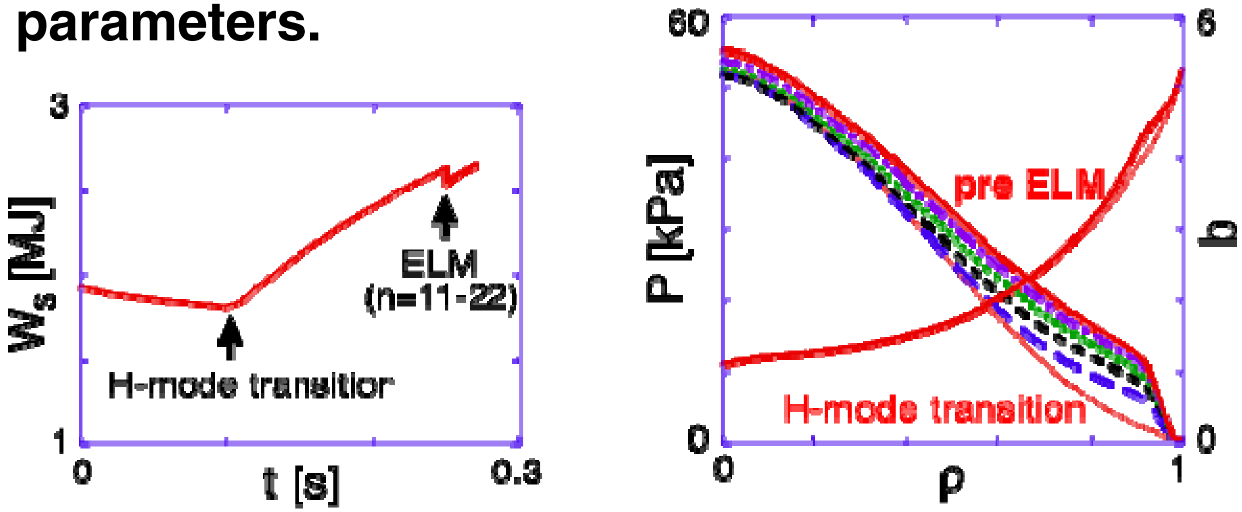
Parallel heat conduction and equipartition energy depend on the collisionality.

ELM energy loss simulation

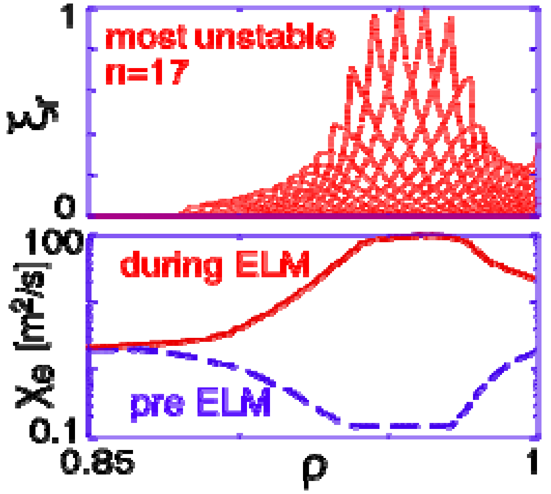
Integrated modelling in JT-60U

- **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.

Transient behavior of core-pedestal-SOL-divertor plasmas along pedestal growth and ELM crash

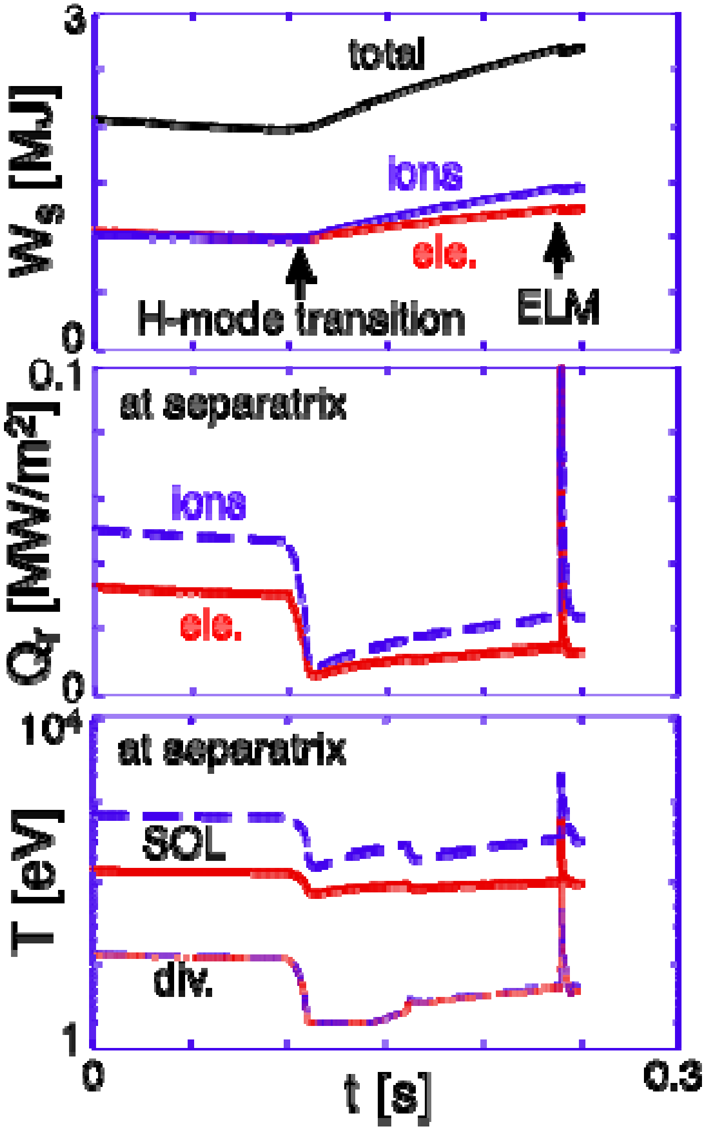
Integrated modelling in JAEA

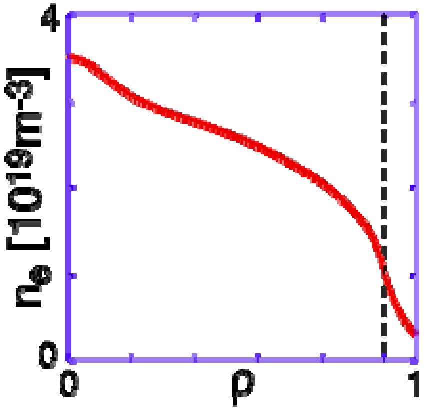
Simulation condition : JT-60U like parameters

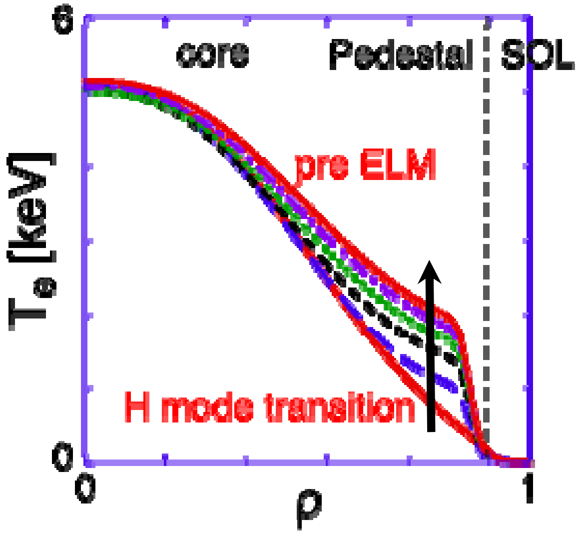
- $R=3.4$ m, $a=0.9$ m, $I_p=1.5$ MA, $B_t=3.5$ T, $\kappa\sim1.5$, $\delta\sim0.21$, $Z_{eff}=2.3\text{-}2.8$, $P_{NB}=12$ MW, $\beta_N=0.8\text{-}1$

- ELM duration $\delta t_{ELM} = 200$ μs, diffusivity $\chi_{ELM}^{max}=100$ m^2/s, Pedestal width $\Delta_{PED} = 0.05$

- Fixed density profile, $n_{div}=1\text{x}10^{20}$ m^{-3} (High recycling divertor)





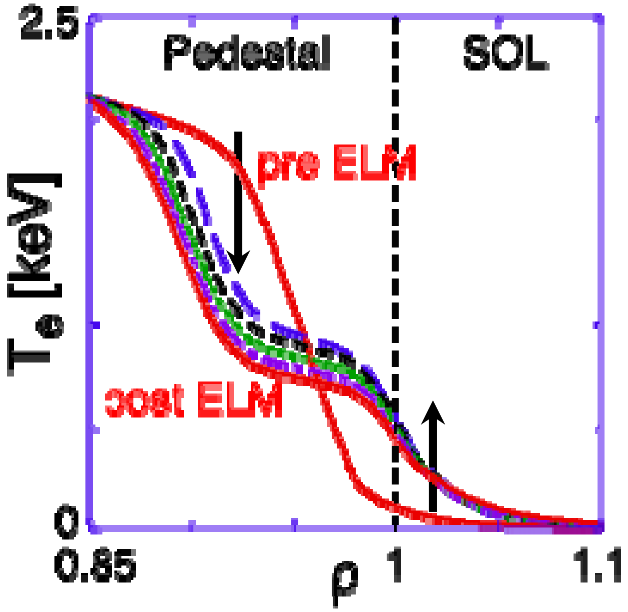


Increase of SOL temperature mitigates the radial edge gradient and lowers the ELM energy loss.

Energy flows into the SOL and the SOL-divertor temperatures rapidly increases.

The resultant energy loss (< 10% of W_{ped}) is comparable with that in JT-60U.

Electron energy loss is larger than the ion one, due to larger heat conduction parallel to the magnetic field.



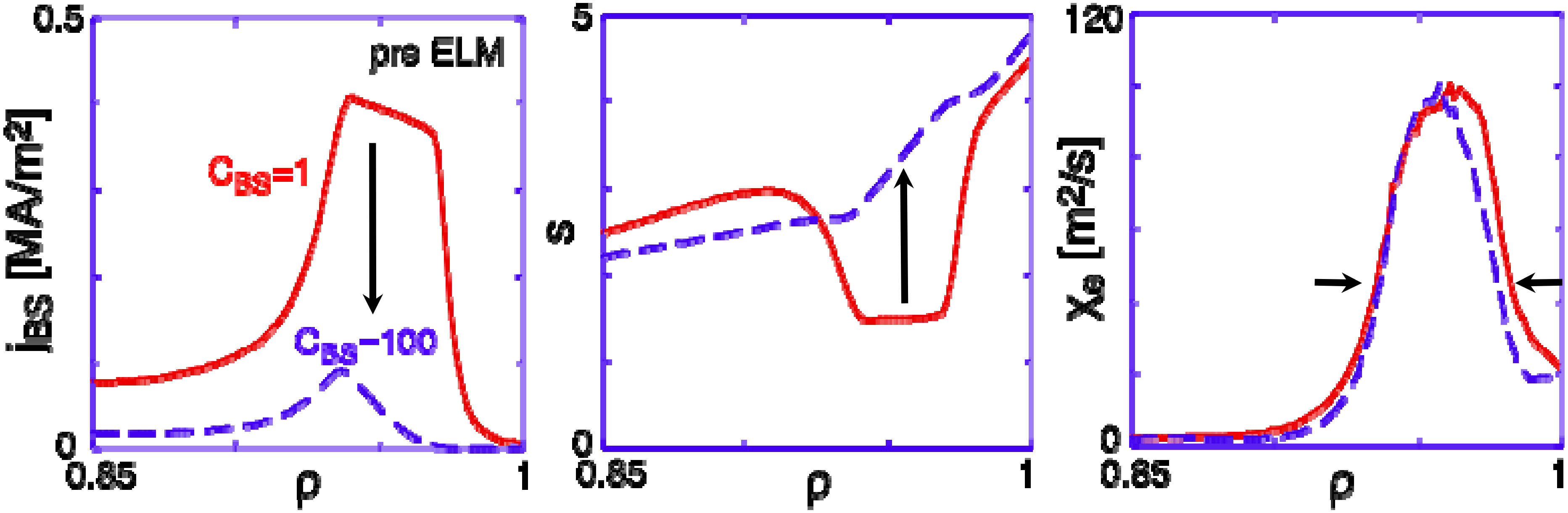
By the integration of the SOL model, the consistent analysis was obtained.

a) Bootstrap current effect

The collisionality in the bootstrap current model is artificially enhanced by C_{BS}=100 (enhanced collisionality: $\nu^*_{ped}= C_{BS}\,\nu^*_{ped0}= 9$).

Bootstrap current decreases with increasing the collisionality and intensifies the magnetic shear at the pedestal region.

The increase of magnetic shear reduces the width of eignfunctions of unstable modes.

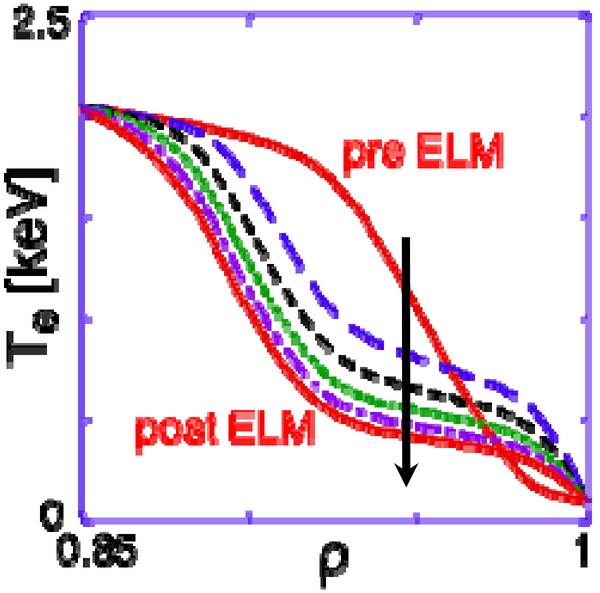


ELM energy loss is reduced by increasing collisionality in bootstrap current.

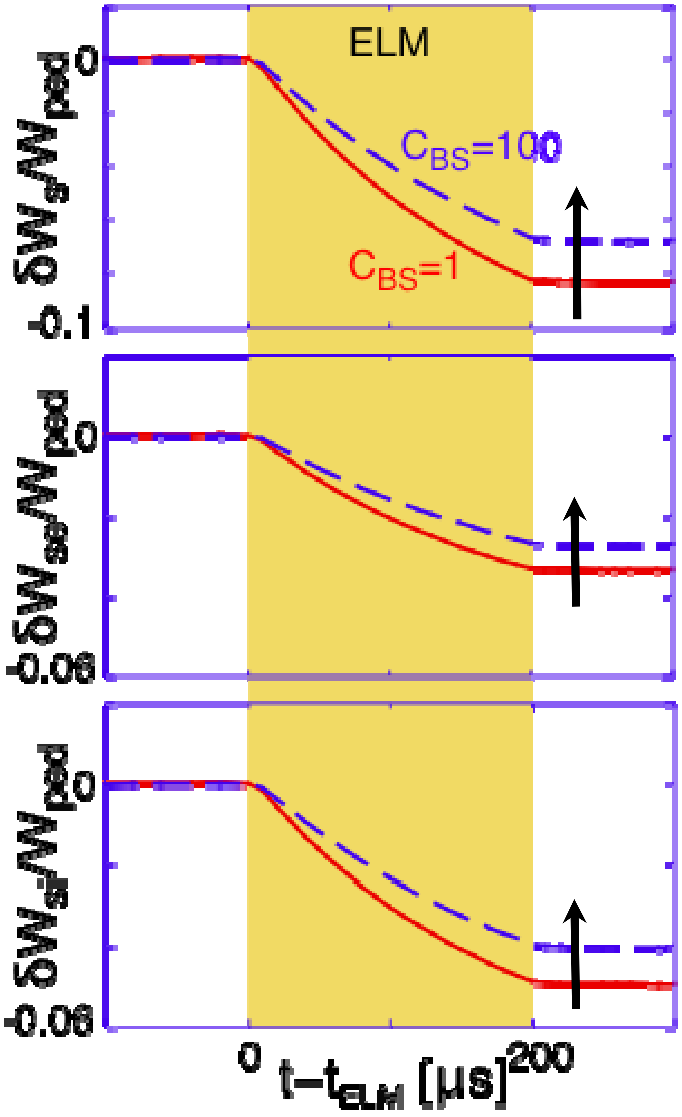
Integrated modelling in JAEA

Simulation condition : T_{SOL}=100 eV, SOL model is not used to clear only the bootstrap current effect.

Both electron and ion energy losses are reduced in almost the same ratio.



fixed B.C.
w/o SOL model



b) SOL transport effects

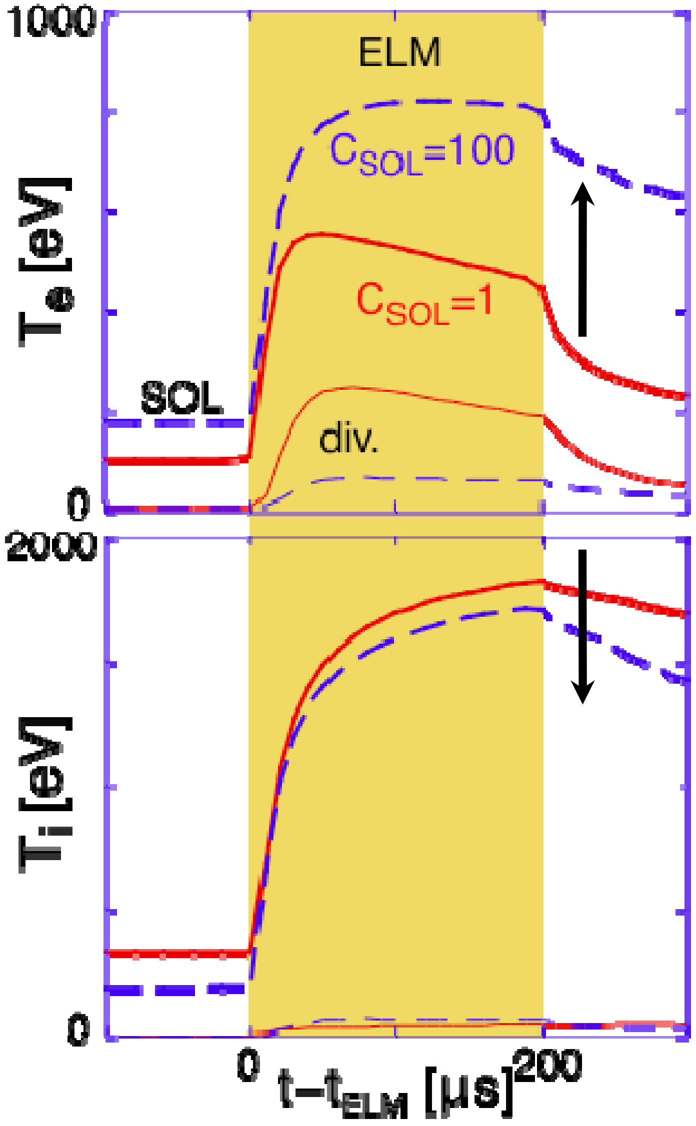
Integrated modelling in JAEA

The collisionality in SOL model is artificially enhanced by C_{SOL}=100 (ν^*_{ped}= 9).

SOL electron temperature increases with the collisionality, because the parallel heat conduction is inversely proportional to the collisionality.

SOL ion temperature decreases with increasing the collisionality, because the equipartition energy flows is proportional to the collisionality.

SOL electron temperature increases with collisionality, while ion one decreases.



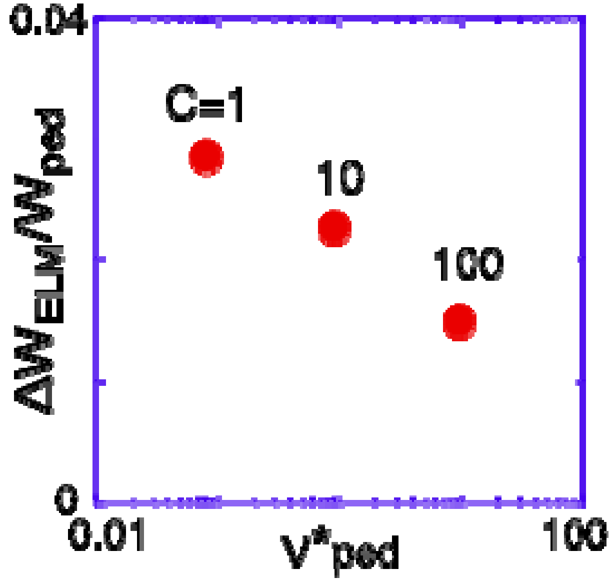
c) Both effects of bootstrap current and SOL transport on ELM energy loss

Integrated modelling in JAEA

Collisionality in both models is enhanced by $C=C_{BS}=C_{SOL}$.

When the collisionality is enhanced by C=100, the electron energy loss is reduced by about 1/3, but the ion one is reduced a little.

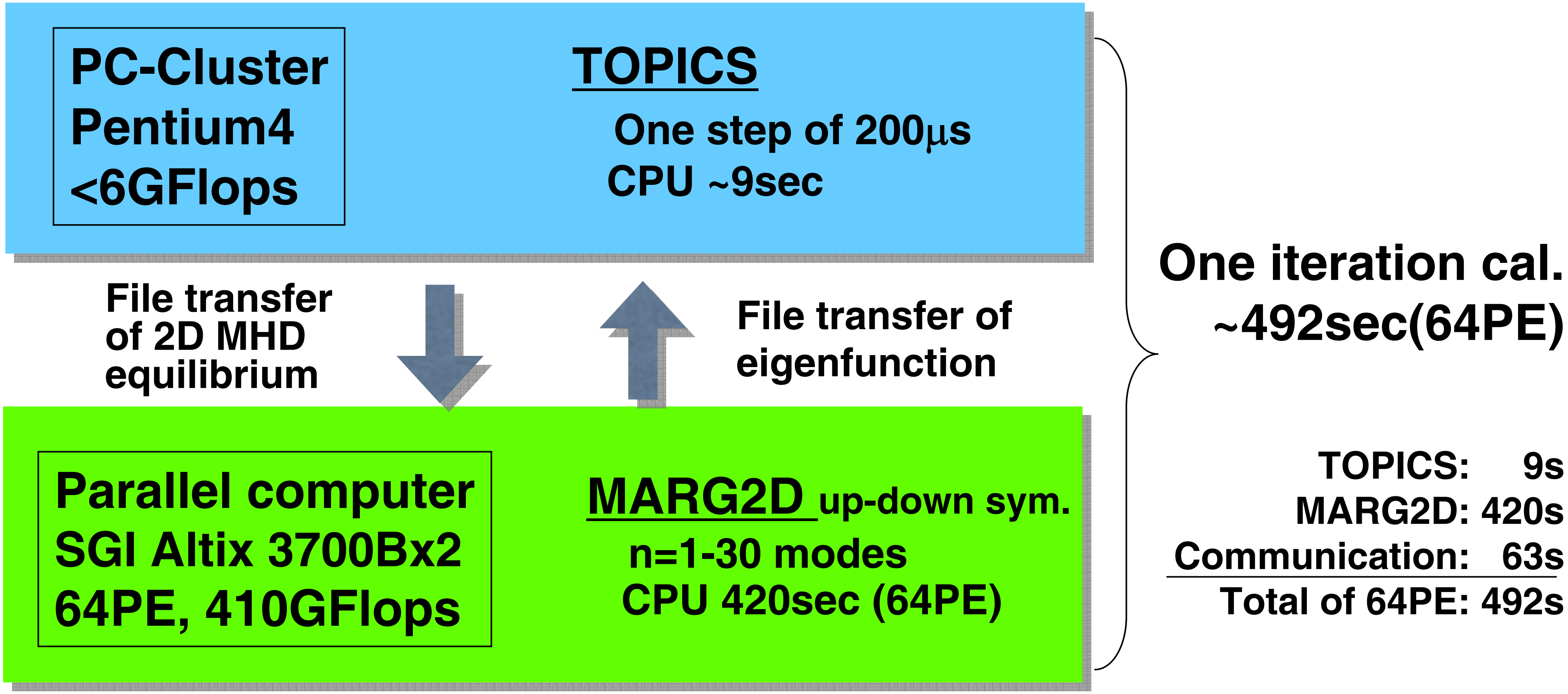
Total energy loss is reduced about half.



By the above two mechanisms, the ELM energy loss decreases with increasing the collisionality. The bootstrap current and the SOL transport have the major effect on the collisionality dependence.

Vaule of $\Delta W_{ELM}/W_{ped}$~0.05 was measured in JT-60U plasmas with ν^*_{ped}~0.1.

Computer system and calculation time on Integrated calculation of ELM



PC-Cluster
Pentium4
<6GFlops

TOPICS

One step of 200μs
CPU ~9sec

File transfer of 2D MHD equilibrium

File transfer of eigenfunction

Parallel computer
SGI Altix 3700Bx2
64PE, 410GFlops

MARG2D up-down sym.

n=1-30 modes
CPU 420sec (64PE)

One iteration cal.
~492sec(64PE)

TOPICS: 9s
MARG2D: 420s
Communication: 63s
Total of 64PE: 492s

- Estimated cal. time is 136.7hours (5.7days) for 200msec simulation for 200μs iteration, using 64PE.

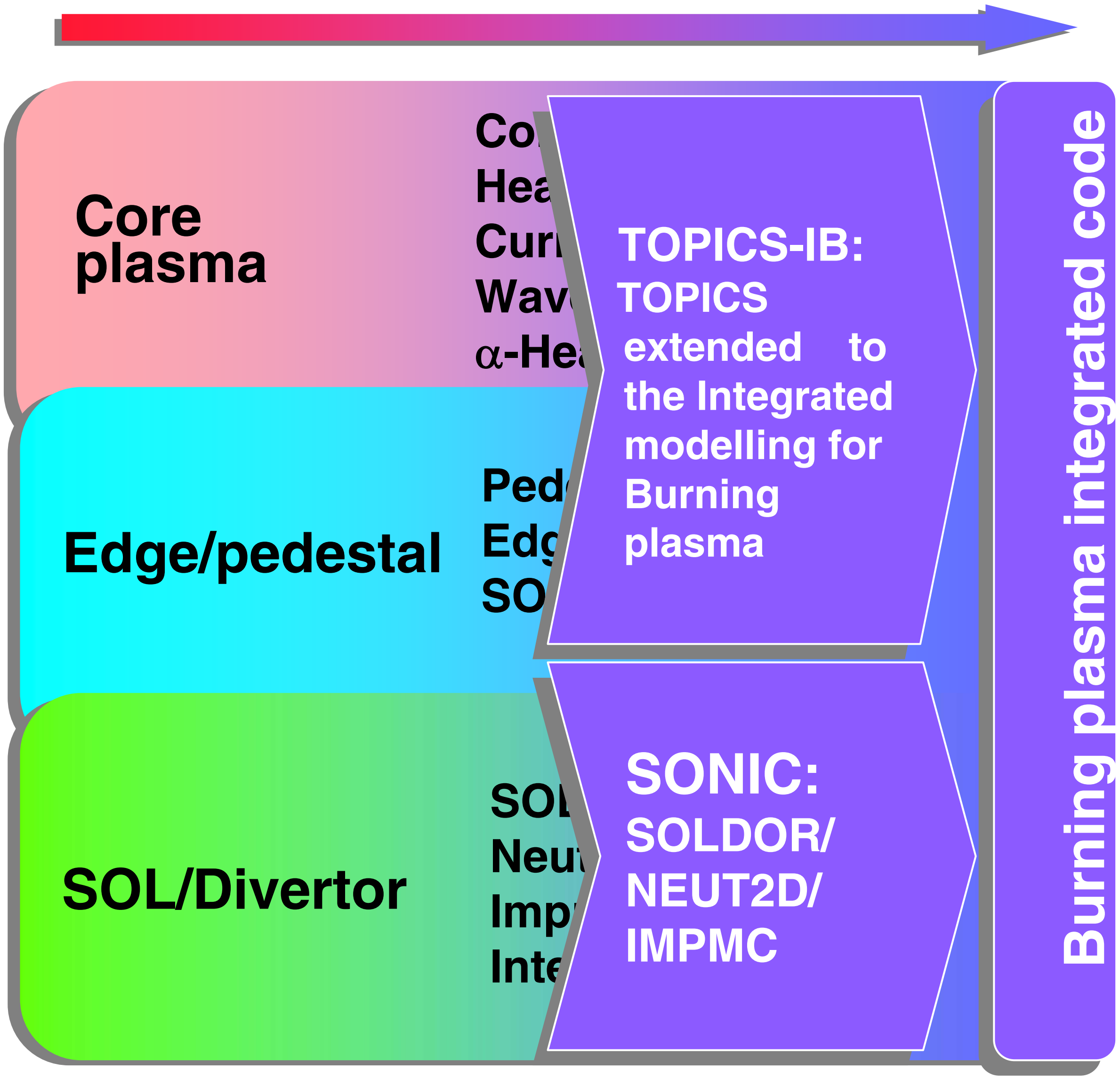
3. Summary

Integrated code TOPICS-IB has been developed, presented here, based on the 1.5D transport code with the MHD stability model.

- ✓ **NTM model has been developed with the integration of the transport code, the ECCD code and the modified Rutherford equation. Stabilizing effects of NTM by ECCD were clarified by the consistent analysis. Optimization of EC profile was obtained.**
- ✓ **The ideal MHD stability code MARG2D has been developed for the low and high n stability with a short CPU time.**
- ✓ **Using the MARG2D as the ELM mode, the integrated model of the pedestal-ELM-SOL has been developed.**
- ✓ **The Integrated model has been clarified self-consistent effects of ELM energy loss on the collisionality.**

Consistent analysis by the integrated code are useful to investigated the complex plasma and control the integrated performance.

Plan for integration of whole plasma



Core plasma

Co
Hea
Cur
Wav
α-Hea

Edge/pedestal

Ped
Edg
SO

SOL/Divertor

SOL
Neut
Imp
Inte

TOPICS-IB:
TOPICS extended to the Integrated modelling for Burning plasma

SONIC:
SOLDOR/
NEUT2D/
IMPMC

Burning plasma integrated code

Two ways for whole plasma simulation of burning plasma

1) TOPICS-IB will extend to the divertor region:
  - **Dynamic response**
  - **Simple divertor model**
  - **Transport model is key**

2) SONIC will extend to the core region:
  - **Accurate divertor model**
  - **2D transport model**

The construction of integrated model according the purpose of research is important.

Appendix

Background

- Burning plasma has very wide time and spatial scales, and complex physics such as Turbulence, Transport, MHD, Wave-particle interaction, Plasma-wall interaction, Atomic and molecular physics
- Control of complex plasmas is the big issue:
    - High confinement, High beta, High bootstrap, High radiation, Suppression of impurity, α-heating dominant
    - Strong coupling of pressure, current and momentum profiles
  - – Control of autonomous plasmas
  - – Control of the burning of the fusion reaction

To solve these issues:

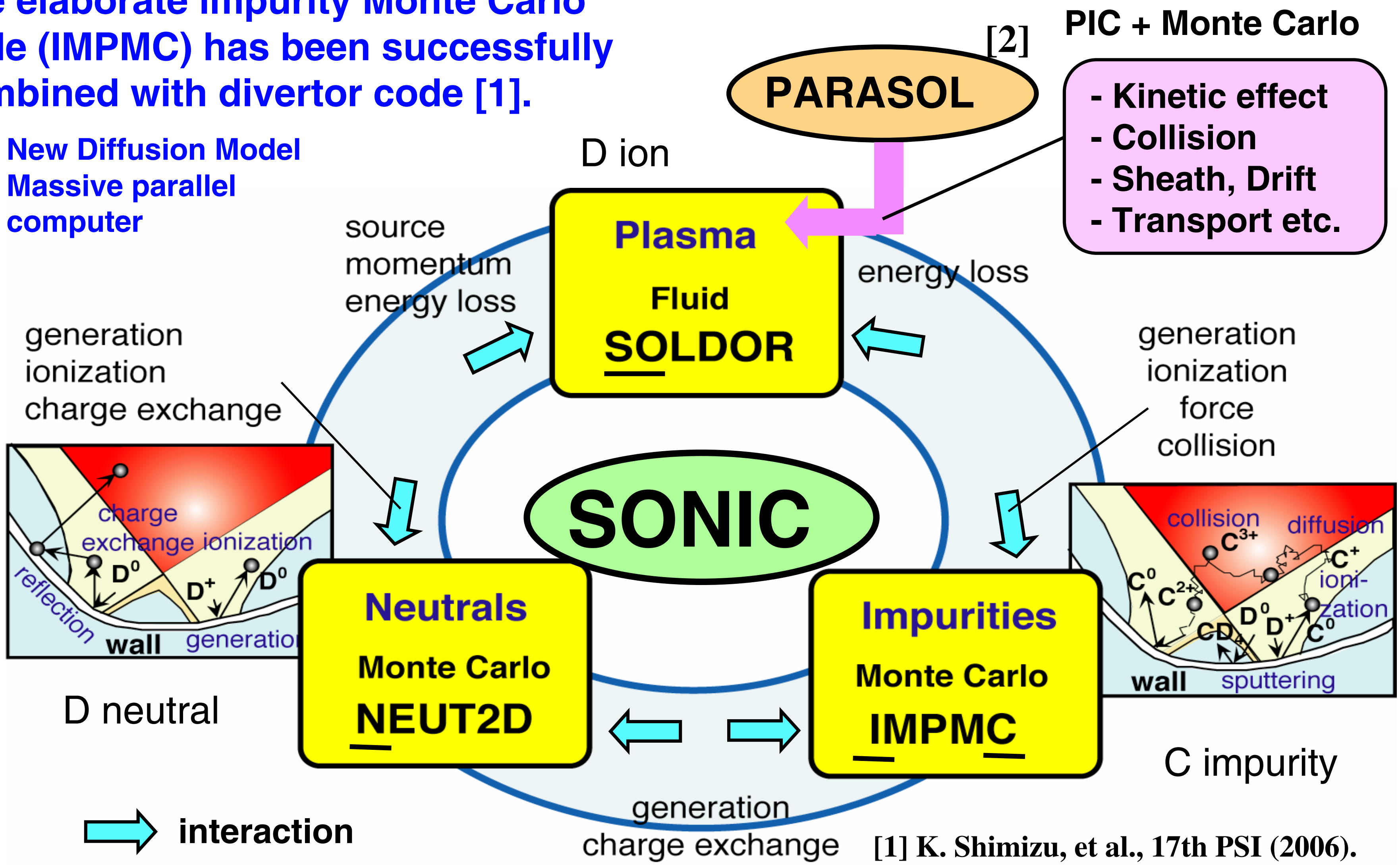
- It is not realistic to simulate the whole burning plasma based on the first principle at the present.
- Modeling and integration of the model are a useful method for the complex burning plasma.

Integrated SOL-divertor code:SONIC

Integrated modelling in JT-60U

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

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



PIC + Monte Carlo [2]

PARASOL

- **Kinetic effect**
- **Collision**
- **Sheath, Drift**
- **Transport etc.**

D ion

Plasma
Fluid
SOLDOR

source
momentum
energy loss

energy loss

generation
ionization
charge exchange

generation
ionization
force
collision

SONIC

Neutrals
Monte Carlo
NEUT2D

D neutral

Impurities
Monte Carlo
IMPMC

C impurity

generation
charge exchange

➡ **interaction**

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

Plasma Potential Energy of the Ideal MHD Model (Background2)

On the basis of the ideal MHD model, the plasma potential energy can be expressed as

$$W_p = \frac{1}{2}\int\int\int \boxed{\frac{1}{\mu_0}|\mathbf{Q}_\perp|^2} + \boxed{\frac{1}{\mu_0}\left|Q_{//}\mathbf{b} - \mu_0\frac{\xi\cdot\nabla p}{B^2}\mathbf{B}\right|^2} + \boxed{\Gamma p|\nabla\cdot\xi|^2}$$

$$\boxed{-\frac{\mathbf{j}\cdot\mathbf{B}}{B^2}(\xi\times\mathbf{B})\cdot\mathbf{Q}}\boxed{-2(\xi\cdot\nabla p)(\xi\cdot\kappa)}\sqrt{g}\,d\tau,$$

$$\mathbf{Q} := \mathbf{Q}_\perp + Q_{//}\mathbf{b} = \nabla\times(\xi\times\mathbf{B}), \quad \kappa := (\mathbf{b}\cdot\nabla)\mathbf{b}.$$

- **The first, second, and third terms are the stabilizing terms called the Shear Alfven term, the Compressional Alfven term, and the sound wave term, respectively.**
- **The third and fourth terms are the destabilizing terms driven by the parallel current and the pressure gradient.**
- **A kink-ballooning mode and a peeling-ballooning mode are destabilized by the coupling of both current and pressure terms.**

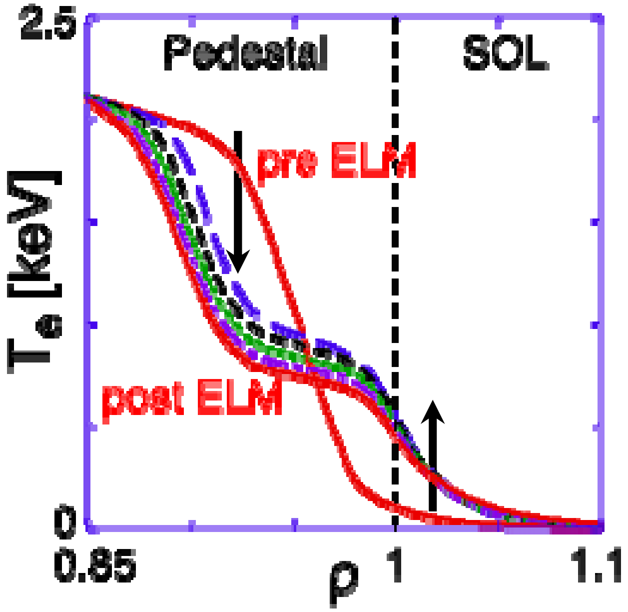
Increase of SOL temperature mitigates the radial edge gradient and lowers the ELM energy loss.

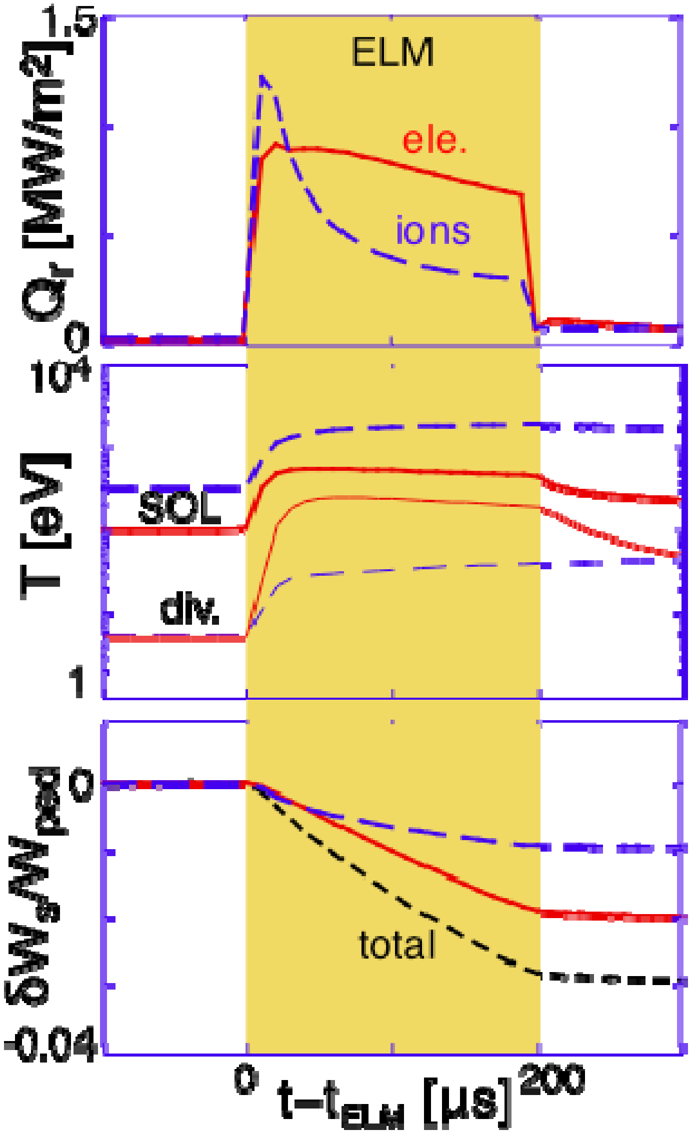
Integrated modelling in JAEA

Energy flows into the SOL and the SOL-divertor temperatures rapidly increases.

The resultant energy loss (< 10% of W_{ped}) is comparable with that in JT-60U.

Electron energy loss is larger than the ion one, due to larger heat conduction parallel to the magnetic field.





ELM energy loss is reduced by increasing collisionality in SOL transport.

Integrated modelling in JAEA

For higher collisionality, the SOL electron temperature increases more and the electron energy loss is reduced.

On the contrary, the SOL ion temperature decreases and the ion energy loss is enhanced a little.

Total ELM energy loss is reduced according to the electron energy loss and the ion contribution is small.