



TOPICSによるシミュレーションの現状

林 伸彦、白井 浩

原研那珂研、炉心プラズマ解析室

平成15年3月17-18日、核燃焼プラズマ統合コード作業会、九大応力研

TOPICS

(TOKamak Prediction and Interpretation Code System)

コンパイル : Fortran 90

実行環境 : IBM SP3, Compaq(Dec) alfa WS, PC Linux, SGI Origin

解析手法 : 定常 (実験解析)

非定常解析 (実験解析、シミュレーション)

実行モジュールは同じで、入力ファイルで切替え

図形出力 : Graphic library : GDlib + Eagle (原研オリジナル)

定常解析 : 計算終了後自動的に図形出力

非定常解析 : ファイル出力し、別のソフトToppltで図形出力

移植性 : 実験解析用ファイル入力と図形出力ルーチン以外は

基本的に修正なしで可能

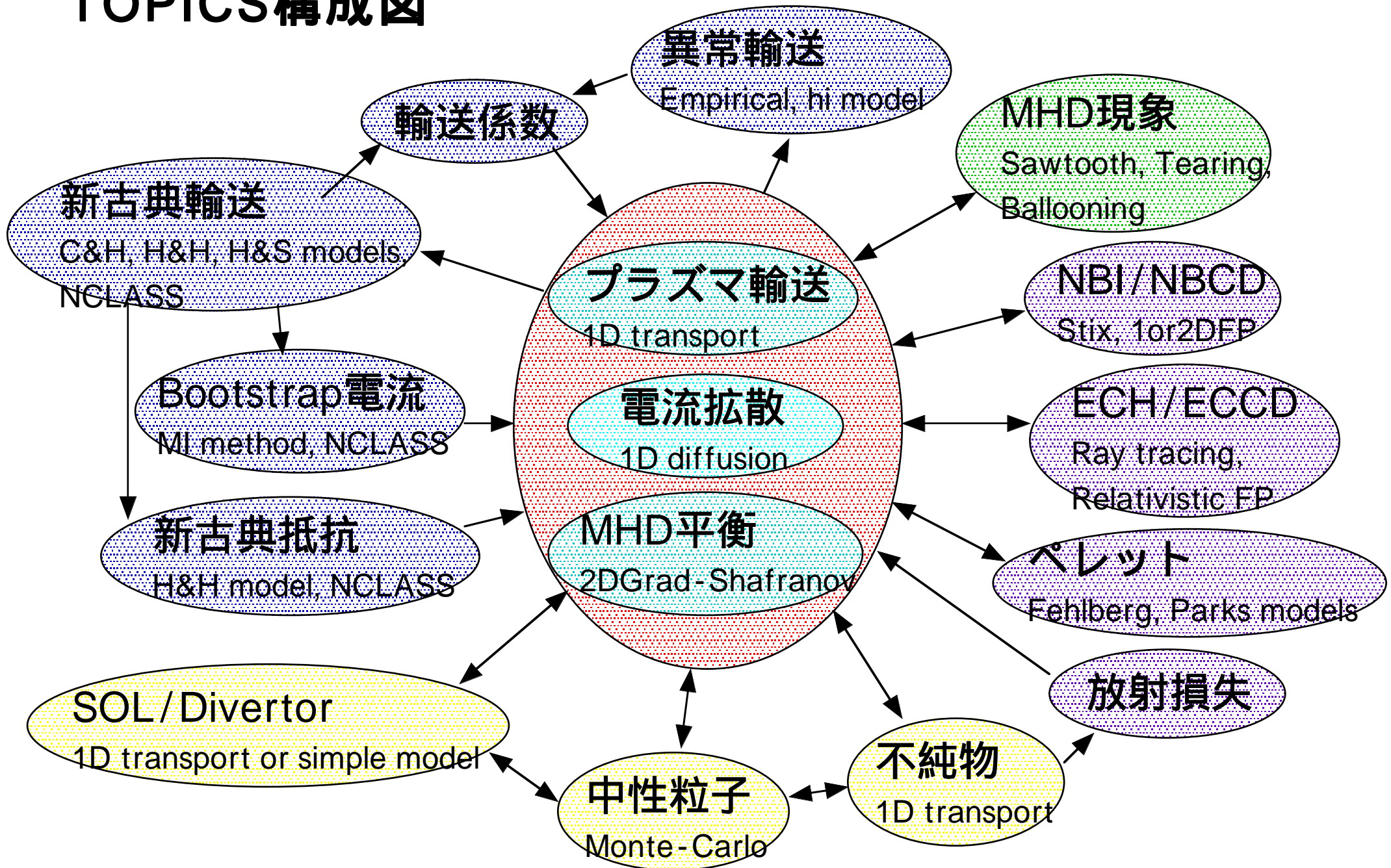
マニュアル : まとまったものはない (計画あるが実行できず)

Web上に資料をまとめ中

各コードとのインターフェース :

基本的に独立させようとしているが完全ではない

TOPICS構成図



TOPICSの構成

プラズマ輸送 (等・不等間隔mesh: 50-400)

トロイダルフラックスで定義された規格化小半径： $\rho = (\Phi(\rho)/\Phi(1))^{0.5}$ ($0 < \rho < 1$)

$$\frac{\partial n_i}{\partial t} = \frac{\partial}{\partial \rho} \left(V' \langle |\nabla \rho|^2 \rangle D_i \frac{\partial n_i}{\partial \rho} \right) + S \quad (\text{多成分イオン可能})$$

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

新古典拡散：

- (1) Chang & Hinton model
- (2) Hinton & Hazeltine model
- (3) Matrix Inversion法 (Hirshman & Sigmar model)
- (4) NCLASS (Houlberg)

異常拡散：

- (1) 経験則 (大河、Kadomtsev)
- (2) Romanelli model

MHD平衡 : MEUDAS (mesh: 128x128, 256x256, 512x512)

2D Grad-Shafranov eq.

Fixed or Free boundary, 固有値 or FCT解法

電流拡散式

$$\frac{\partial}{\partial t} \left(\rho \frac{\partial \Psi}{\partial \Phi} \right) = \frac{\partial}{\partial \rho} \left\{ D \frac{\partial}{\partial \rho} \left(E \frac{\partial \Psi}{\partial \Phi} \right) - S \right\}$$

新古典抵抗 : Hirshman & Hawryluk model (or NCLASS)

Bootstrap電流 :

Matrix Inversion法 (係数はHirshman & Sigmar model)
(or NCLASS)

NBI : Stix定常解 or 1D or 2D Fokker-Planck eq.

NBCD : Mikkelsen model (Stix & 1DFP)

Polevoi (ASTRA) model (2DFP)

ECH/ECCD : Ray tracong and Relativistic Fokker-Planck eq.

中性粒子 : Monte-Carlo法

不純物輸送 : Full charged impurity ion
or IMPACT (fluid eqs. + NCLASS)

放射損失 : Given profile or Calculated from carbon $L_z(T_e)$
or IMPACT

ペレット : Fehlbeg model or Parks model (including ExB drift)

MHD現象 : Sawtooth : Kadomtsev model

Tearing mode : Cylinder model for stability index Δ'

Modified Rutherford eq. for island width

Ballooning mode : Stability analysis

SOL / Divertor : IMPACT or five-point model (予定)

Modified Rutherford equation

$$\frac{\mu_0}{\eta} \frac{dW}{dt} = \underbrace{k_1(\Delta' - \alpha W) \langle |\nabla \rho|^2 \rangle}_{\text{Classical}} + \underbrace{k_2 \mu_0 L_q j_{BS} \left\langle \frac{|\nabla \rho|}{B_p} \right\rangle \frac{W}{W^2 + W_d^2}}_{\text{Bootstrap}} - \underbrace{k_3 \varepsilon_s^2 \beta_p \frac{L_q^2}{\rho_s L_p} \left(1 - \frac{1}{q^2}\right) \langle |\nabla \rho|^2 \rangle \frac{1}{W}}_{\text{GGJ}}$$

$$- \underbrace{k_4 \varepsilon_s^{1.5} \beta_p \left(\frac{\rho_{pi} L_q}{L_p} \right)^2 \langle |\nabla \rho|^2 \rangle \frac{W}{W^4 + W_p^4}}_{\text{Polarization}} - \underbrace{k_5 \mu_0 \frac{L_q}{\rho_s} \left\langle \frac{|\nabla \rho|}{B_p} \right\rangle \eta_{EC} \bar{j}_{EC} \frac{1}{W^2}}_{\text{EC}}$$

$L_q = q / (dq/d\rho)$, ρ_s : Rational surface position

W : Magnetic island width in ρ coordinate, $\Delta'(W)$: Cylindrical model, $\alpha = (m/\rho_s)^2$

W_d : Finite $\chi_\perp/\chi_\parallel$ effect (R.Fitzpatrick, Phys. Plasmas 2(1995)825.)

W_p : Validity limit of the model, $W_p = \varepsilon_s^{0.5} \rho_{pi}$ assumed (H.Reimerdes, LRP 700/01(2001).)

\bar{j}_{EC} : Averaged EC current, $\bar{j}_{EC} = I_{EC}/\pi a^2$

η_{EC} : Efficiency calculated on assumed island structure
(C.C.Hegna and J.D.Callen, Phys. Plasma 4(1997)2940.)

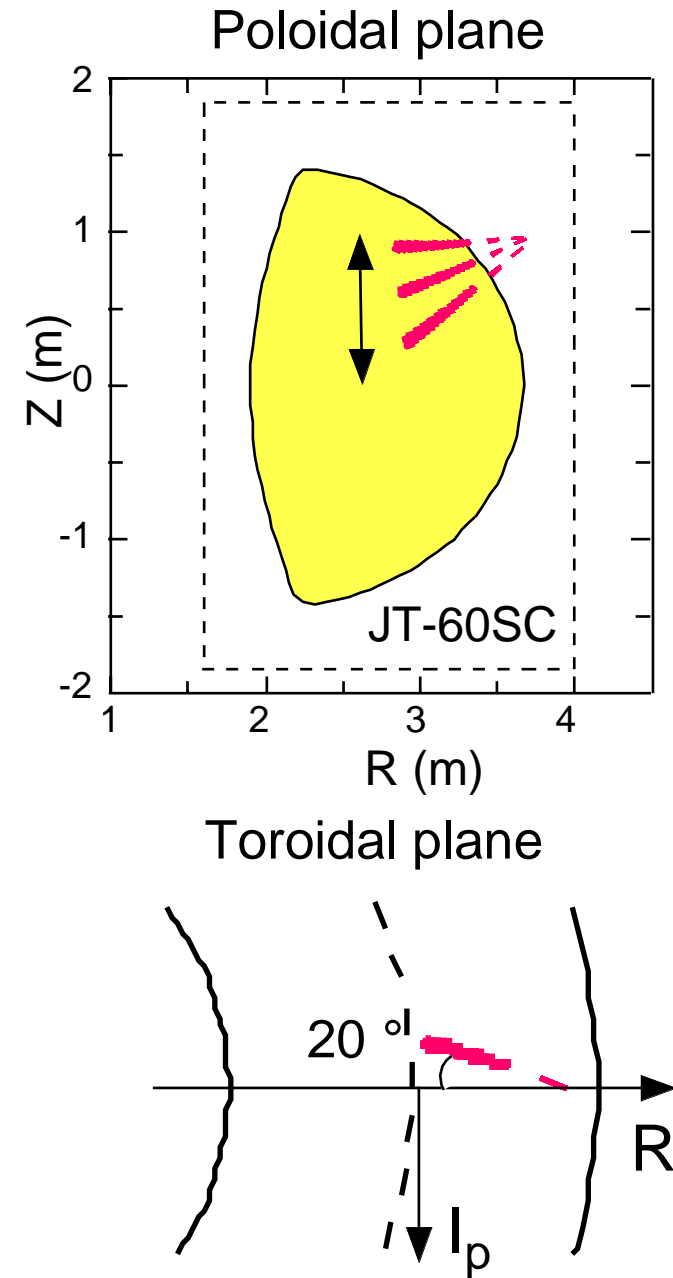
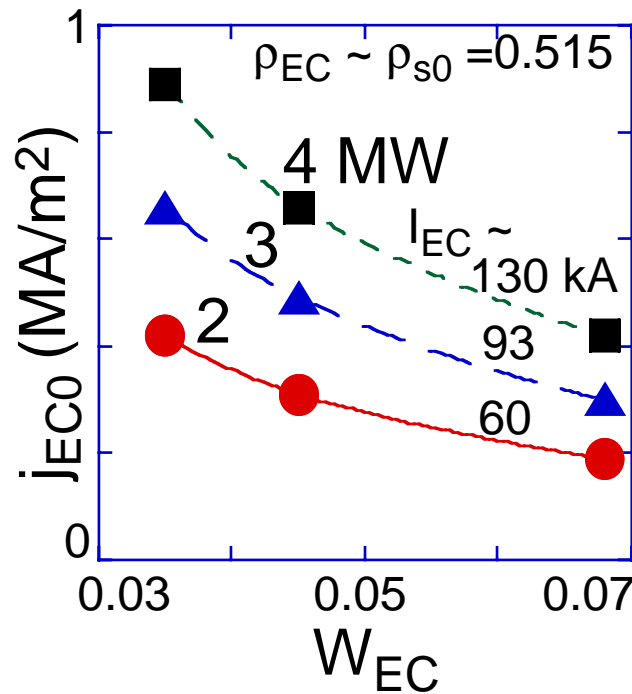
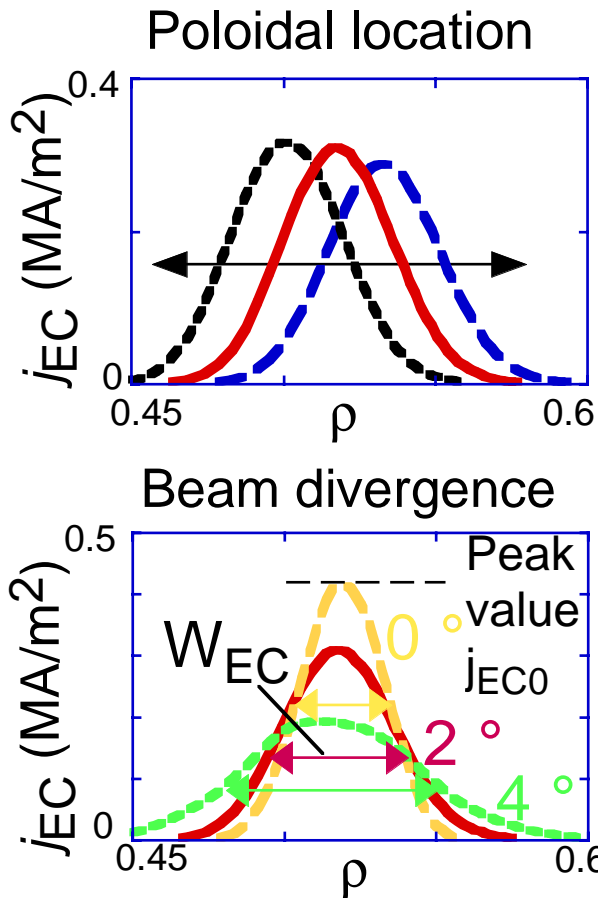
$$\eta_{EC} = \frac{\int d\rho \oint \frac{d\alpha}{2\pi} \cos(m\alpha) \langle j_{EC} \rangle}{\int d\rho \oint \frac{d\alpha}{2\pi} \langle j_{EC} \rangle}$$

ECH/ECCD code (K.Hmamatsu, et al., Plasma Phys.Control. Fusion 42(2000)1309.)

EC ray trajectory : Standard ray tracing method

Profiles of driven current and heating :
Relativistic Fokker-Planck eq.

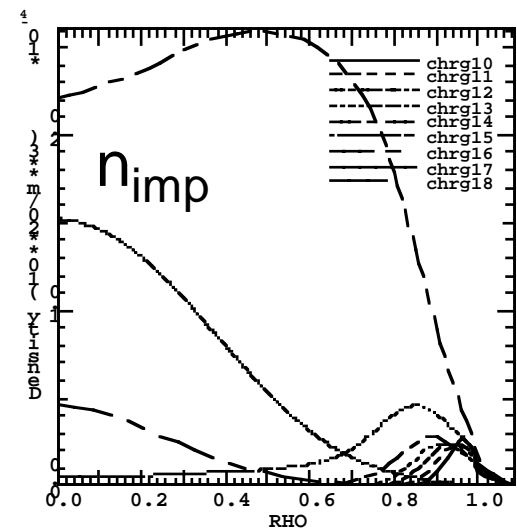
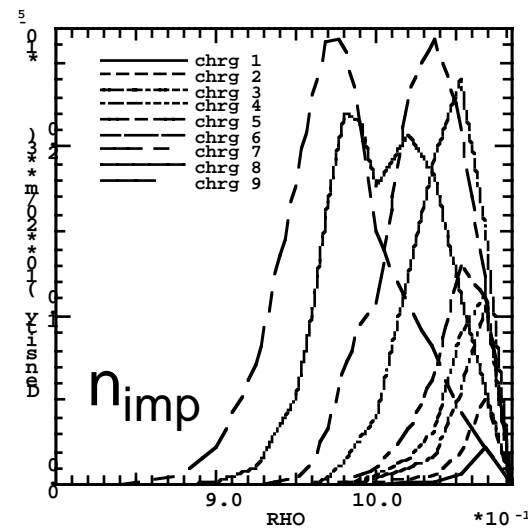
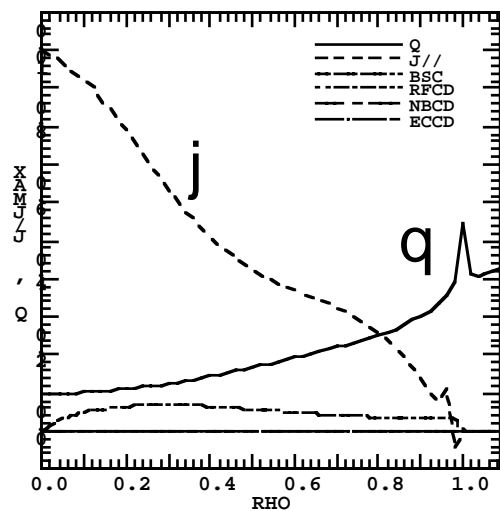
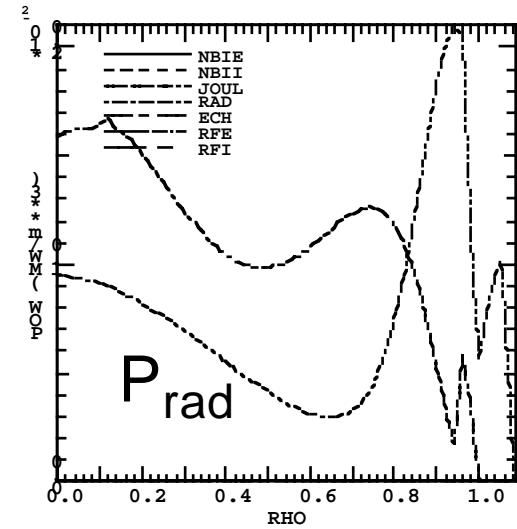
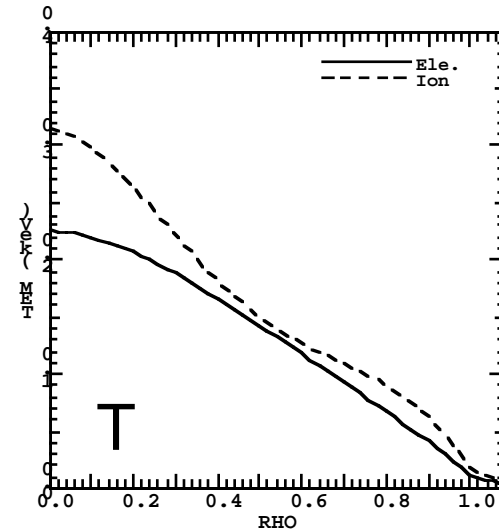
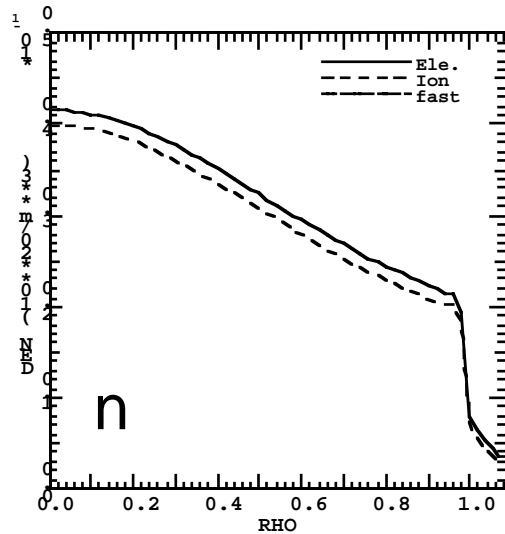
Example :
Fundamental O-mode wave of 110 GHz
No modulation in phase with island rotation



IMPACT (IMPurity Analysis Code for Tokamak plasma)

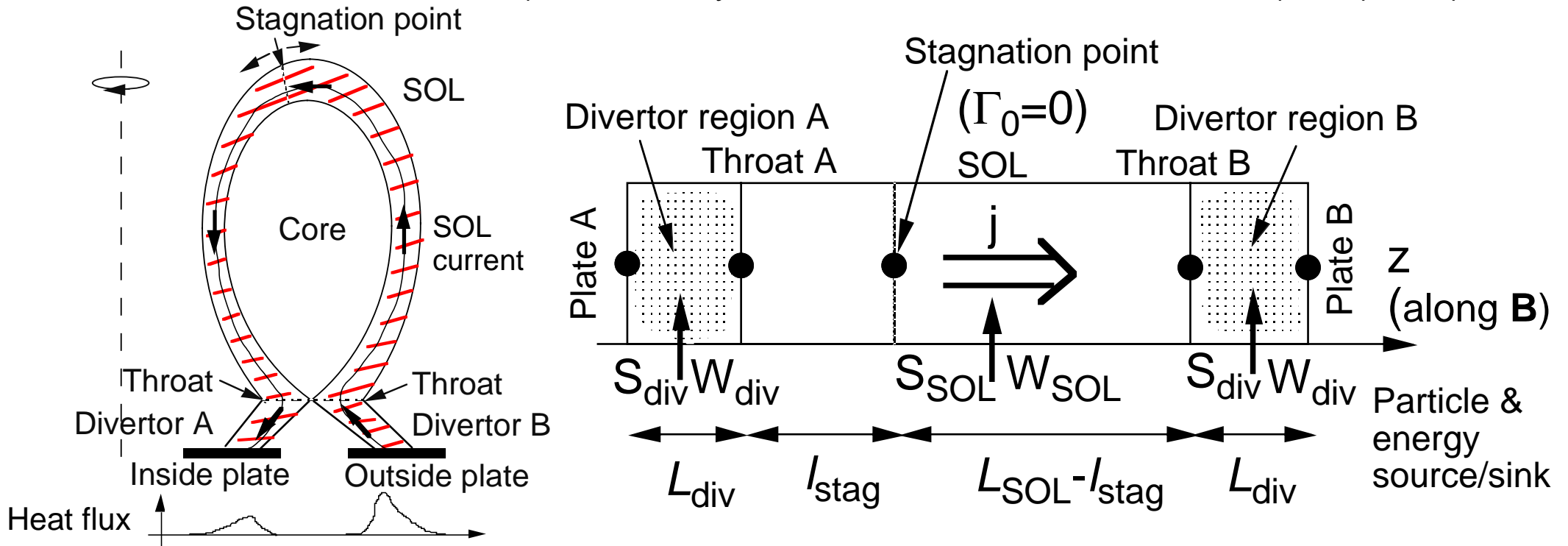
Fluid transport eqs. + 新古典拡散係数(NCLASS)

解析例：定常解析、Ar



ダイバータプラズマ5点モデル

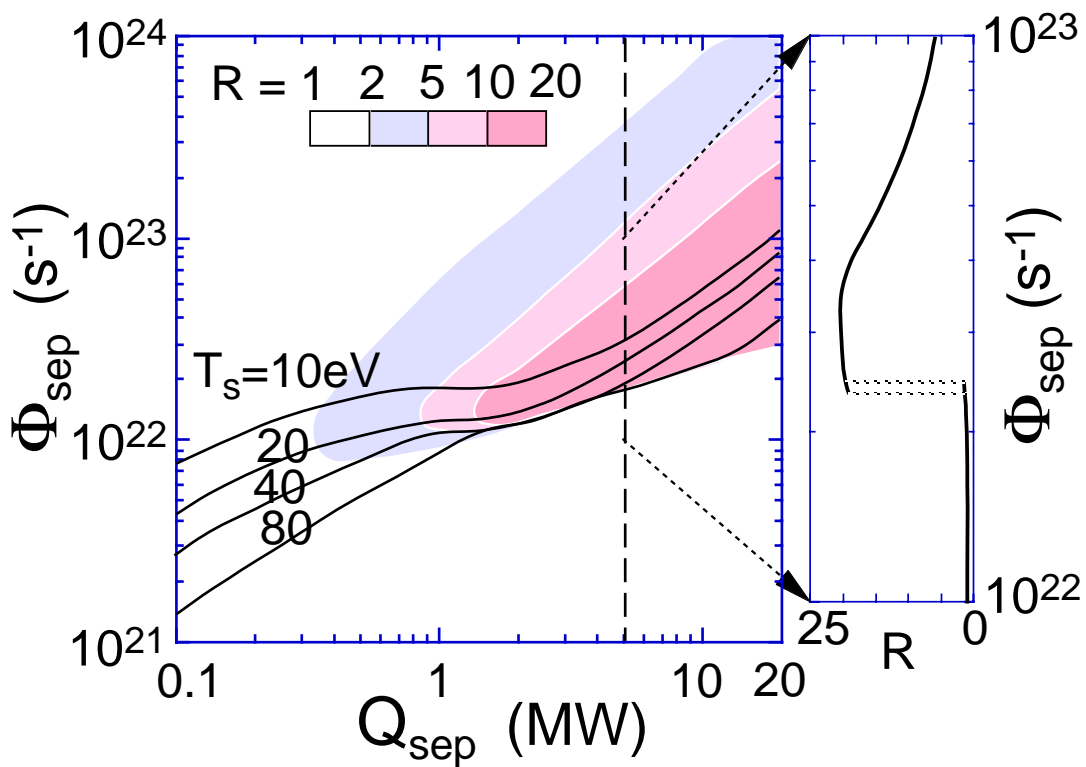
(Ref. : N.Hayashi, et al., J.Nucl.Mater. 266-269 (1999)526.)



- System of model is divided into four regions, i.e., two SOL regions and two divertor regions.
- Fluid equations are integrated along **B** in each region and reduced to a set of nonlinear algebraic equations with physical variables at the five positions.
- All the quantities are those in a magnetic flux tube the nearest to the separatrix.

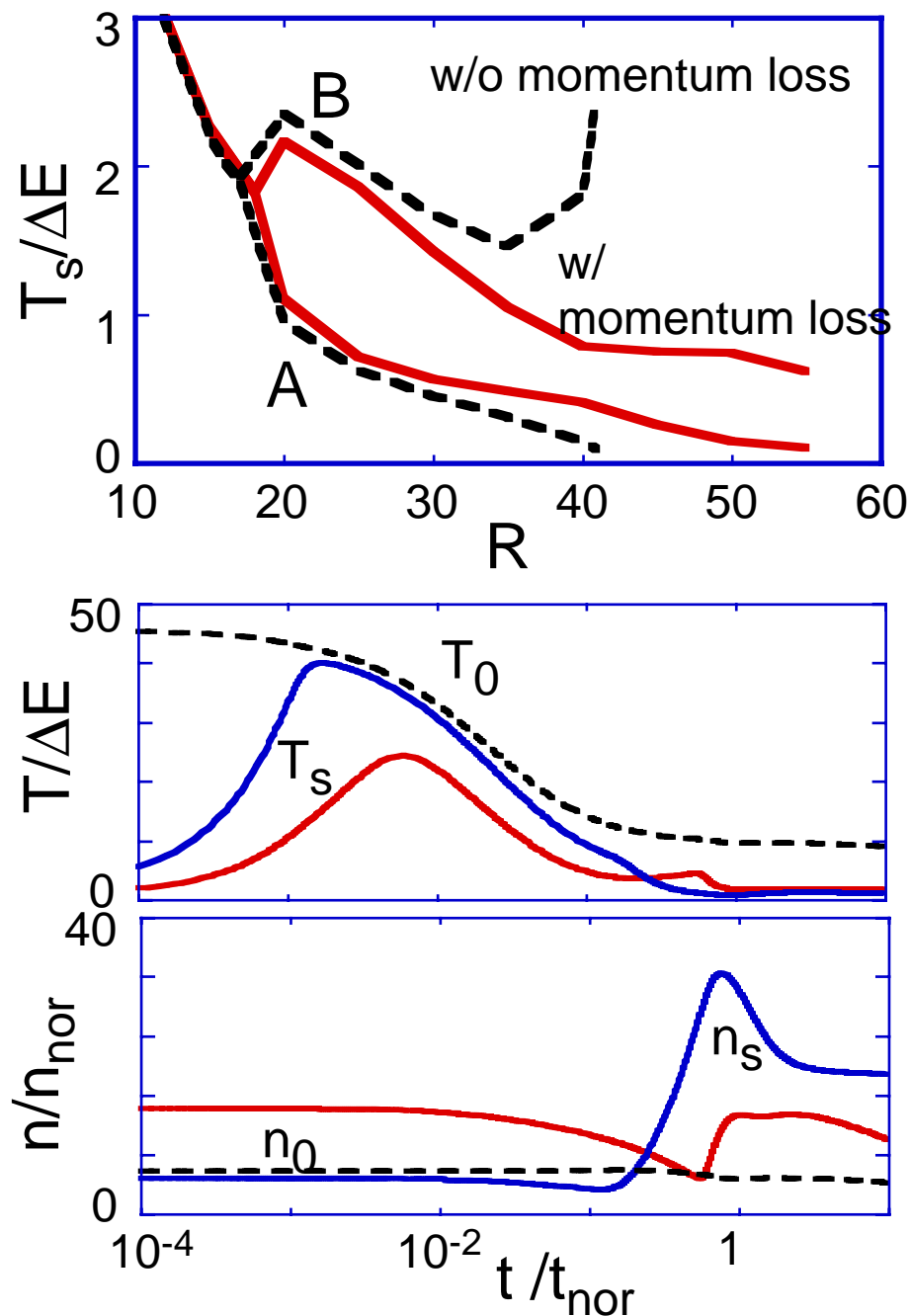
5点モデル結果例

High/Low recycling (symmetric) equilibrium



Dynamic response to ELM particle/heat pulse

Asymmetric equilibrium with current



シミュレーション例 (Tearing stability, sawtooth)

Parameters : $I_p = 1.5 \text{ MA}$, $B_T = 3.5 \text{ T}$, $R = 3.2 \text{ m}$, $a = 0.8 \text{ m}$, $V = 60 \text{ m}^3$, $\kappa = 1.5$, $\delta = 0.1$

$\bar{n}_e = 1.0 \times 10^{19} \text{ m}^{-3}$, $\bar{T}_e \approx 1.8 \text{ keV}$, $\bar{T}_i \approx 1.3 \text{ keV}$, $\beta_p \approx 0.1$, $W_s \approx 0.4 \text{ MJ}$, $P_{OH} \approx 0.7 \text{ MW}$
(Ohmic plasma)

Sawtooth : Kadomtsev model

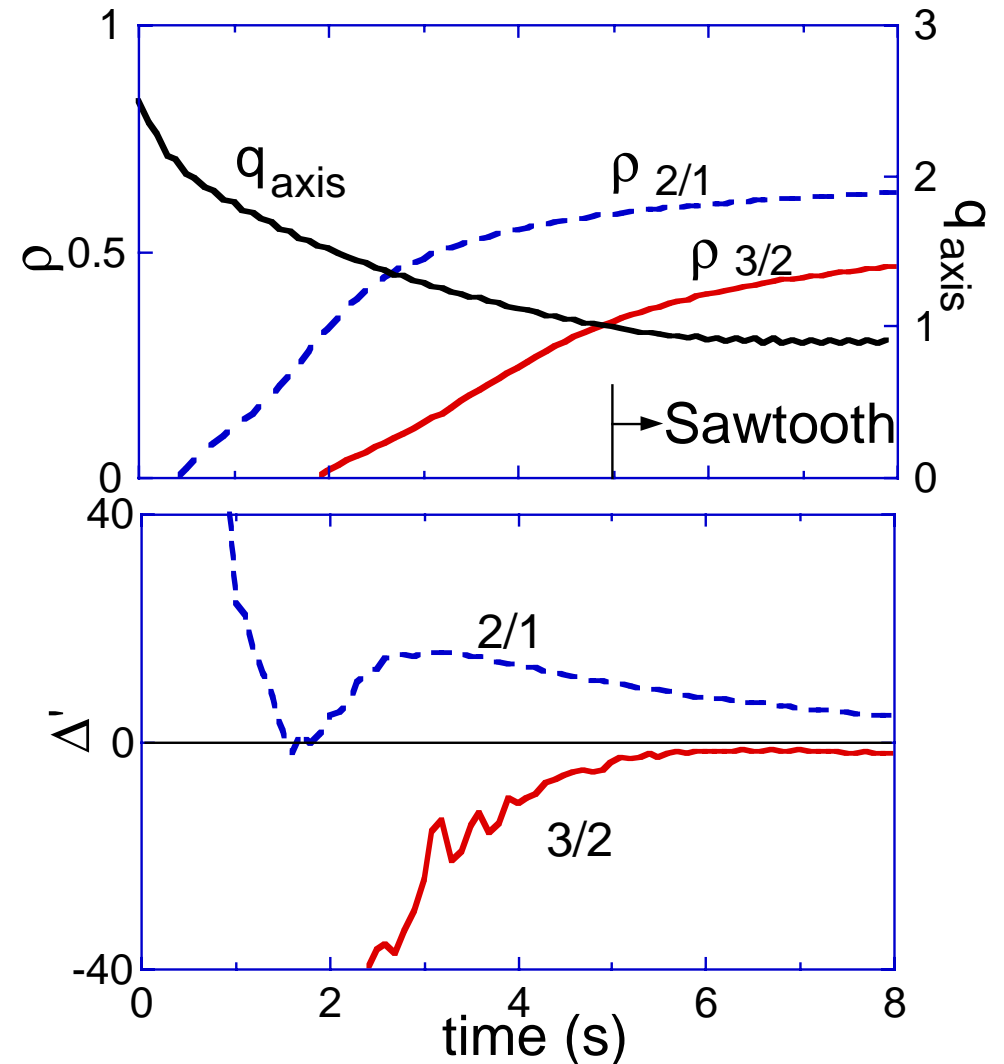
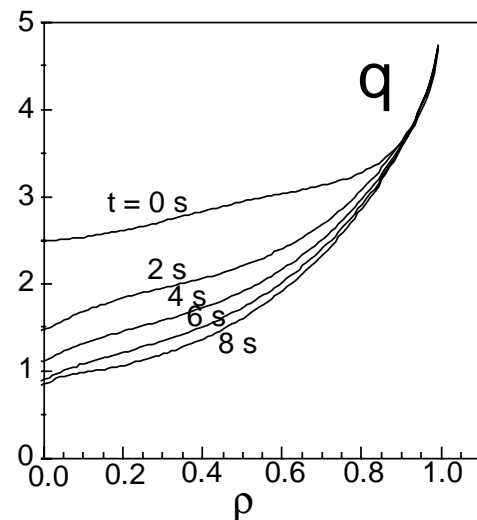
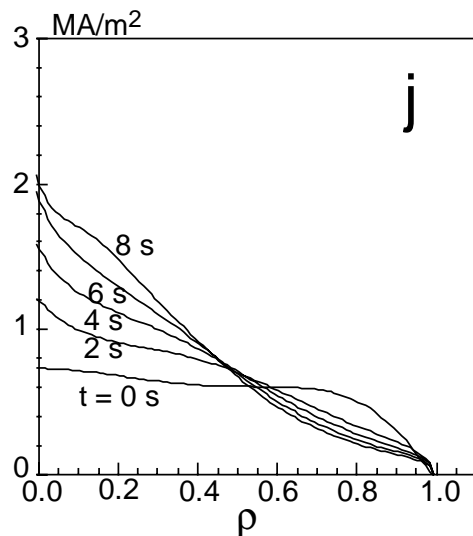
$$\int_0^{\rho_c} \left(\frac{1}{q} - 1 \right) \rho d\rho = 0$$

$$\int_0^{\rho_c} f^{Before} dV = f^{After} \int_0^{\rho_c} dV$$

Density and pressure profiles within $0 < \rho < \rho_c$
are redistributed. (f^{Before} f^{After})

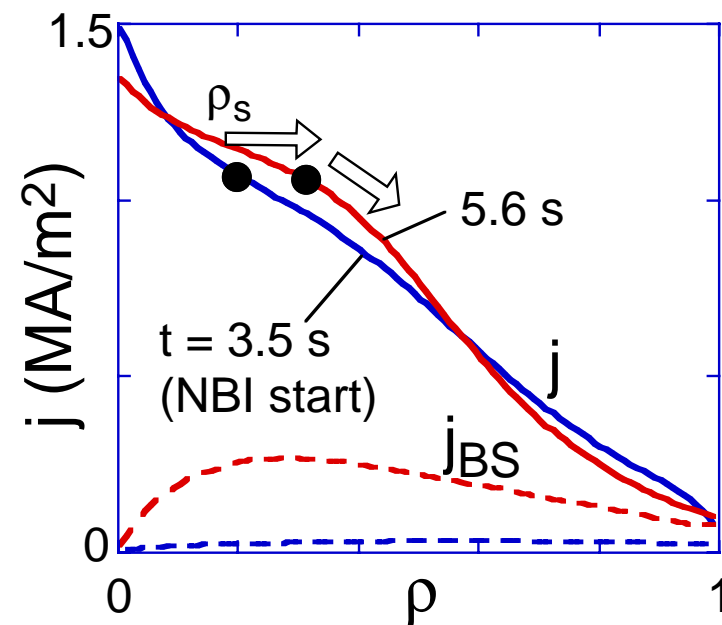
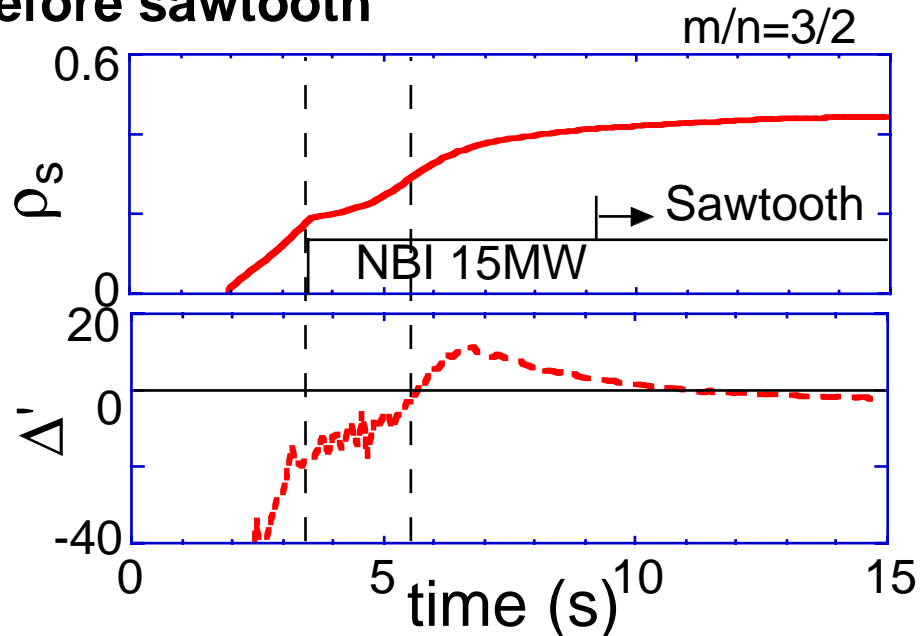
Sawtooth period : 200 ms

Tearing stability index Δ' : Cylinder model

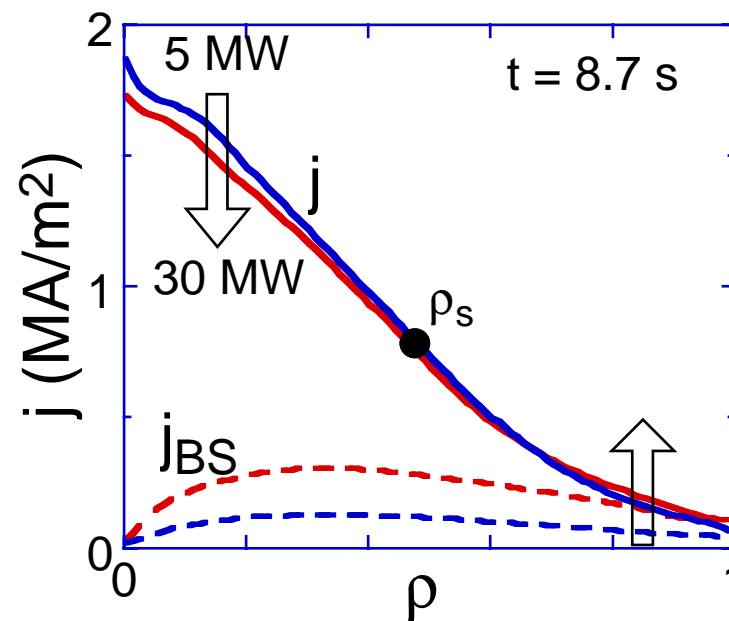
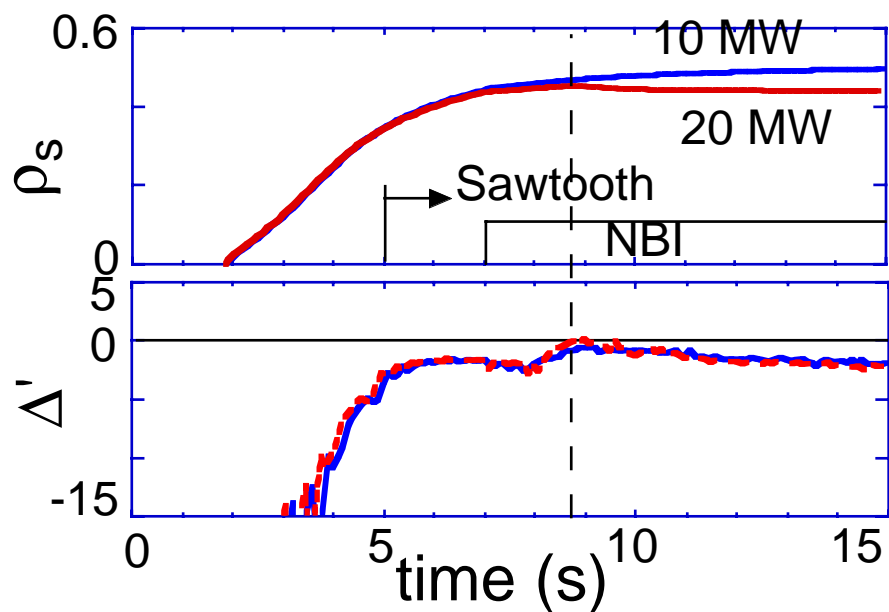


シミュレーション例 (Tearing stability)

NBI before sawtooth



NBI after sawtooth



シミュレーション例 (新古典テアリングモード)

Typical JT-60SC Parameters :

$$I_p=3.0 \text{ MA}, B_T=3.8 \text{ T}, R=2.9 \text{ m}, a=0.85 \text{ m}, P_{\text{NBI}}=30 \text{ MW}, \bar{n}_e=4.2 \times 10^{19} \text{ m}^{-3}, \\ \bar{T}_e=6.4 \text{ keV}, \bar{T}_i=7.5 \text{ keV}$$

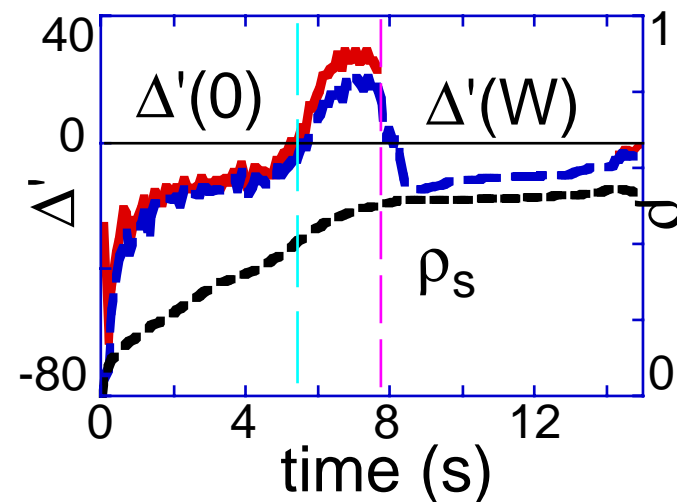
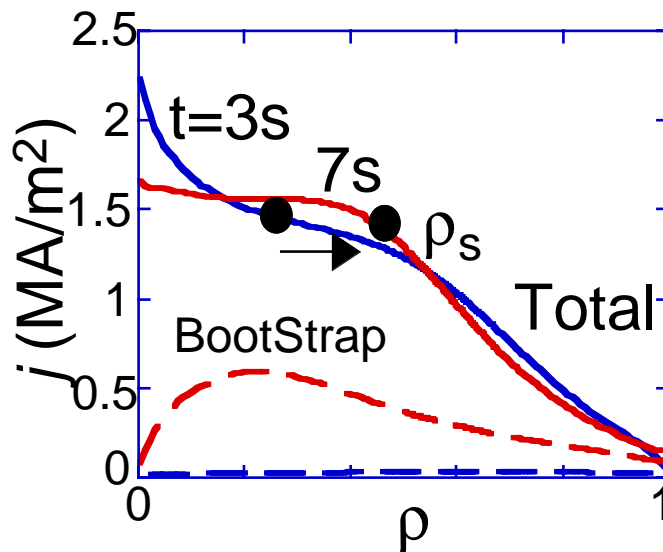
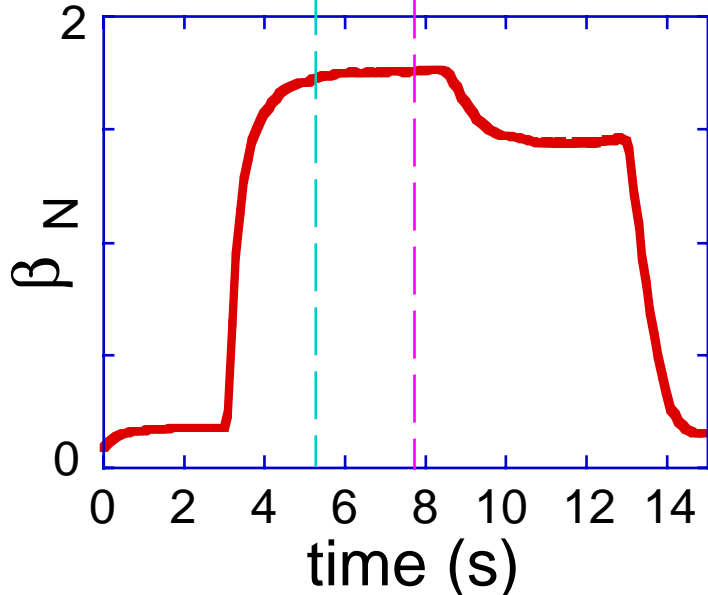
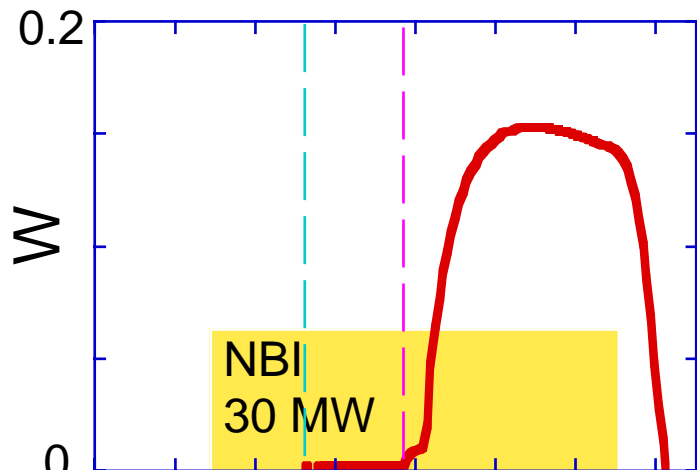
Diffusivities : Empirical model

$$D_i = \chi_e = \frac{\chi_i}{2} = 0.06(1 + 2\rho^2)(1 + P_{\text{NBI}}^{0.5}) \text{ m}^2 / \text{s}$$

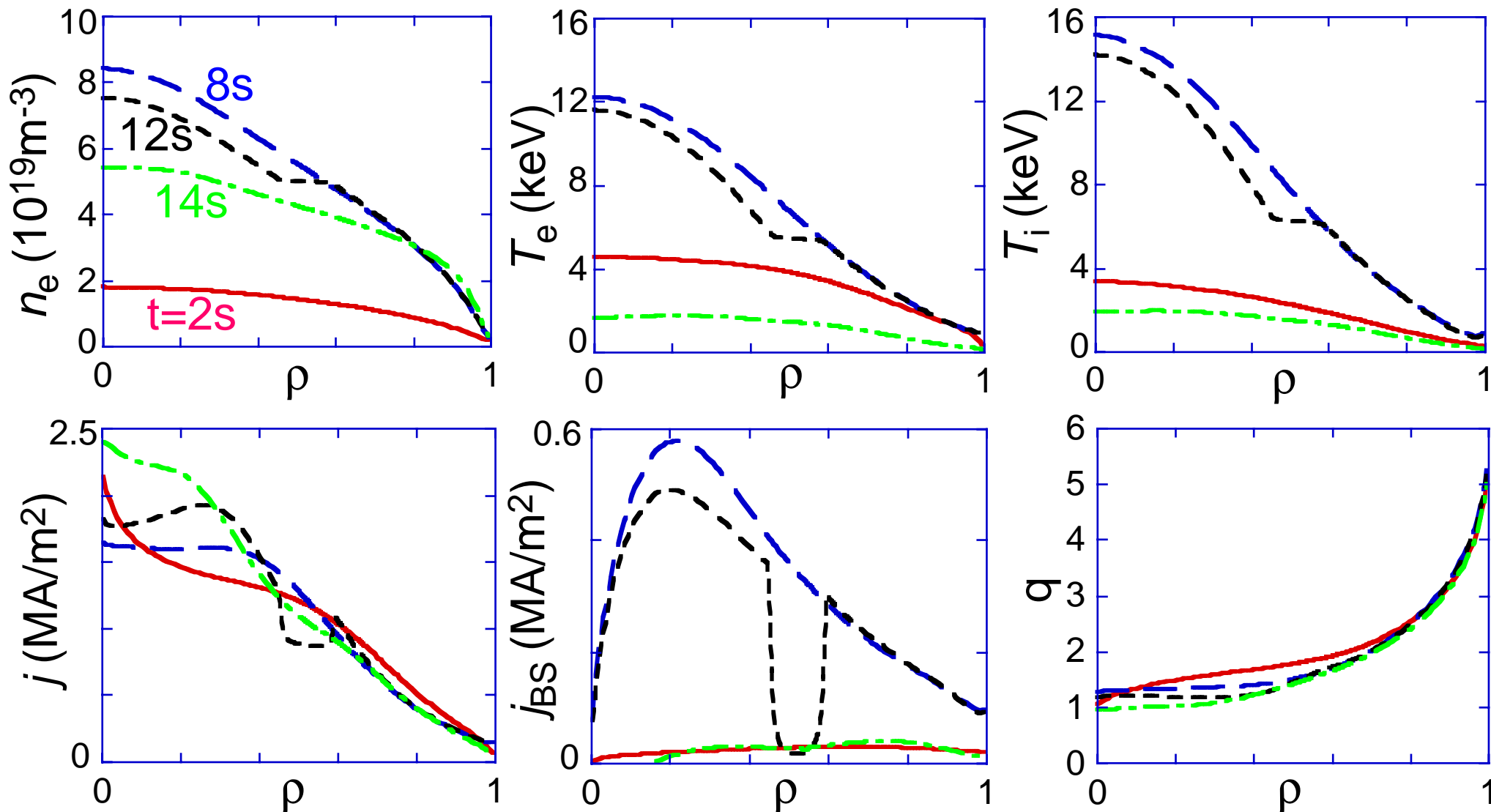
NBI source & Radiation : Fixed profile

Flattening effect : Amplified diffusivities inside island

BS current modifies profile. NTM is triggered by $\Delta' > 0$.



シミュレーション例（新古典テアリングモード）



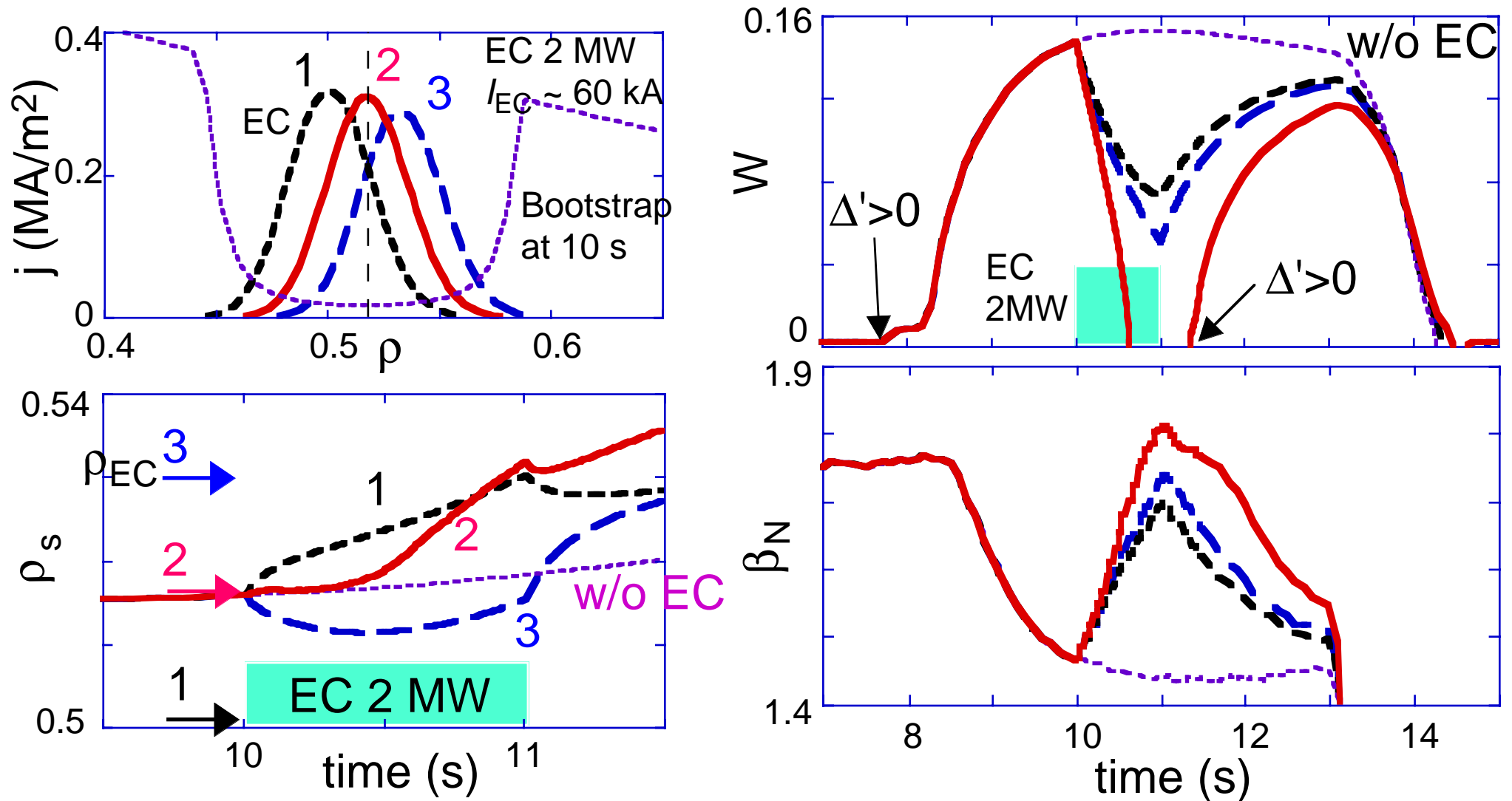
シミュレーション例 (ECCDによるNTM安定化)

NTM is fully stabilized by EC current on the island center.

Off-center EC current can decrease island width, but not fully stabilize NTM.

EC current moves rational surface through background current profile modification.

Decrease stabilizing efficiency of EC



TOPICSシミュレーションの課題

- ・ 異常輸送モデル導入
 - ・ ダイバータモデル導入（5点モデル）
-
- ・ マニュアル
 - ・ 各コードの独立性とインターフェース（ユニット化）
 - ・ 実行環境に依存しない汎用性（主にGraphic lib.の問題）
 - ・ ユーザー不足
 - ・ プログラム改良（goto削除、implicit none等）