TOTAL Simulation of ITER Plasmas

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1. Introduction

History of TOTAL code

Toroidal Transport Analysis Linkage

- Start (~1980)
- Tokamak (2nd stability) 2D+1D

  K.Yamazaki et al., Nuclear Fusion Vol.25 (1985) 1543.
- Helical Analysis 3D+1D

  K.Yamazaki et al., *Nuclear Fusion Vol.32 (1992) 633.*
- Burning Simulation (Tokamak & Helical)

  K.Yamazaki et al., Nuclear Fusion Vol.49 (2009) 055017.

Based on JT-60U ITB operation and LHD e-ITB data.

Main Feature of "TOTAL" is to perform both Tokamak and Helical Analyses

Core Plasma

Equilibrium Tokamak: 2D APOLLO

Helical: 3D VMEC, DESCUR, NEWBOZ

Transport Tokamak: TRANS , GLF23 , NCLASS

Helical: HTRANS, GIOTA

Stability NTM, Sawtooth, Ballooning mode

Edge transport H-mode edge model

Impurity IMPDYN (rate equation) including Tungsten

ADPAC（various cross-section）

Fueling NGS (neutral gas shielding) model

mass relocation model (HFS)

NBI HFREYA, FIFPC

Puffing AURORA

Divertor two-point divertor model,

density feedback control

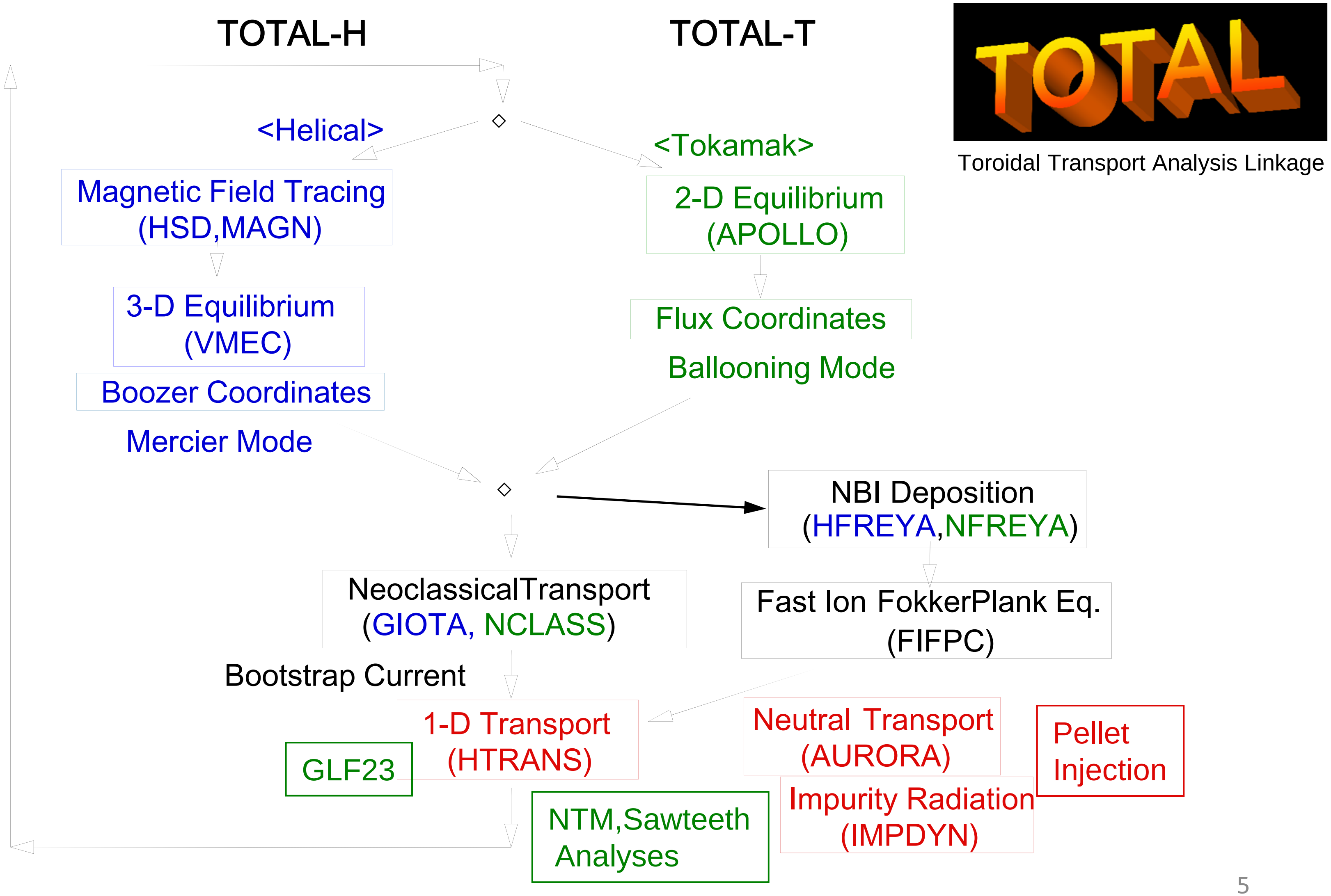
Toroidal Transport Analysis Linkage

World Integrated Modeling

TOTAL-T,-H(J)
TOPICS(J)
TASK(J)
CRONOS(EU)
TRANSP(US)
ASTRA(RU)

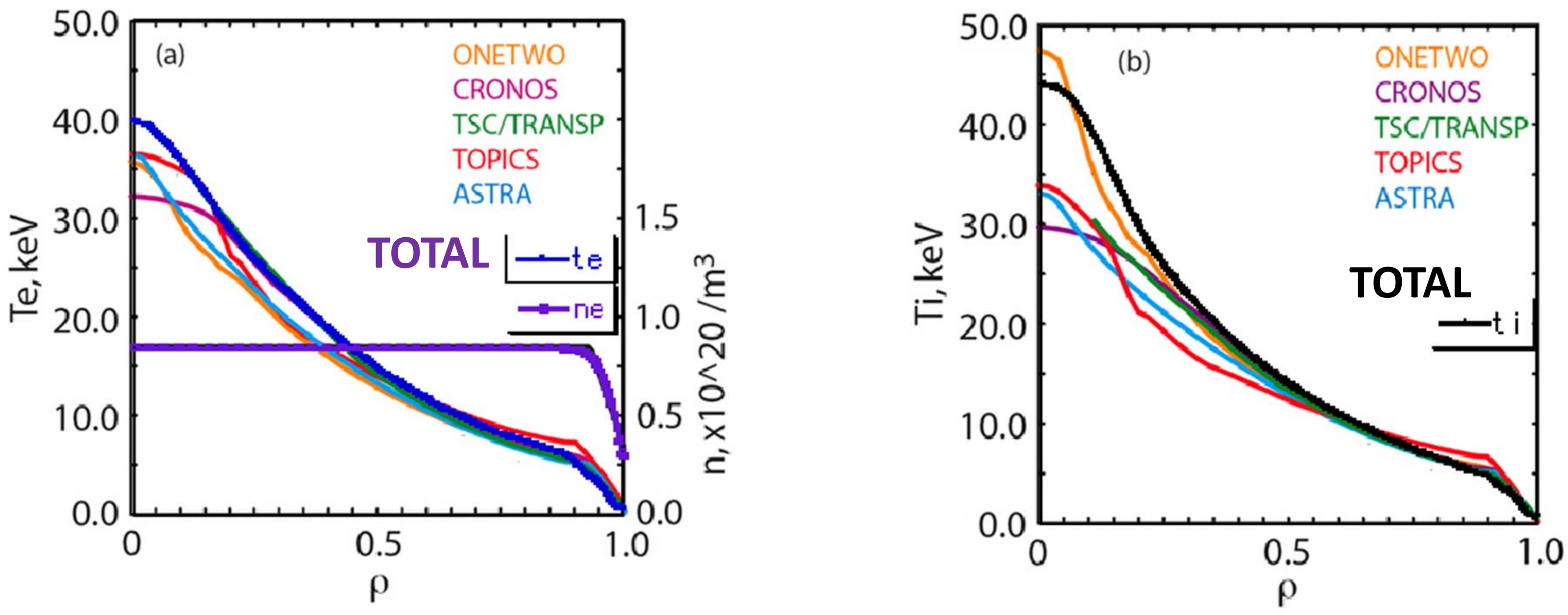
TOTAL Code Development

For Predictive Simulation and Experimental Data Analysis



2. TOTAL Transport Benchmark

TOTAL code CDBM model
(GLF23 model)



Ref: C.E. Kessel et al., Nucl. Fusion 47 (2007) 1274–1284

3. Pellet Injection and ITB Formation

Bohm/GyroBohm Mixed Transport Model

TALA, T., et al., Plasma Phys. Control. Fusion 43 (2001) 507-523.

$$\chi_{e,i} = \chi_{neoclassical} + \chi_{anomalous}$$

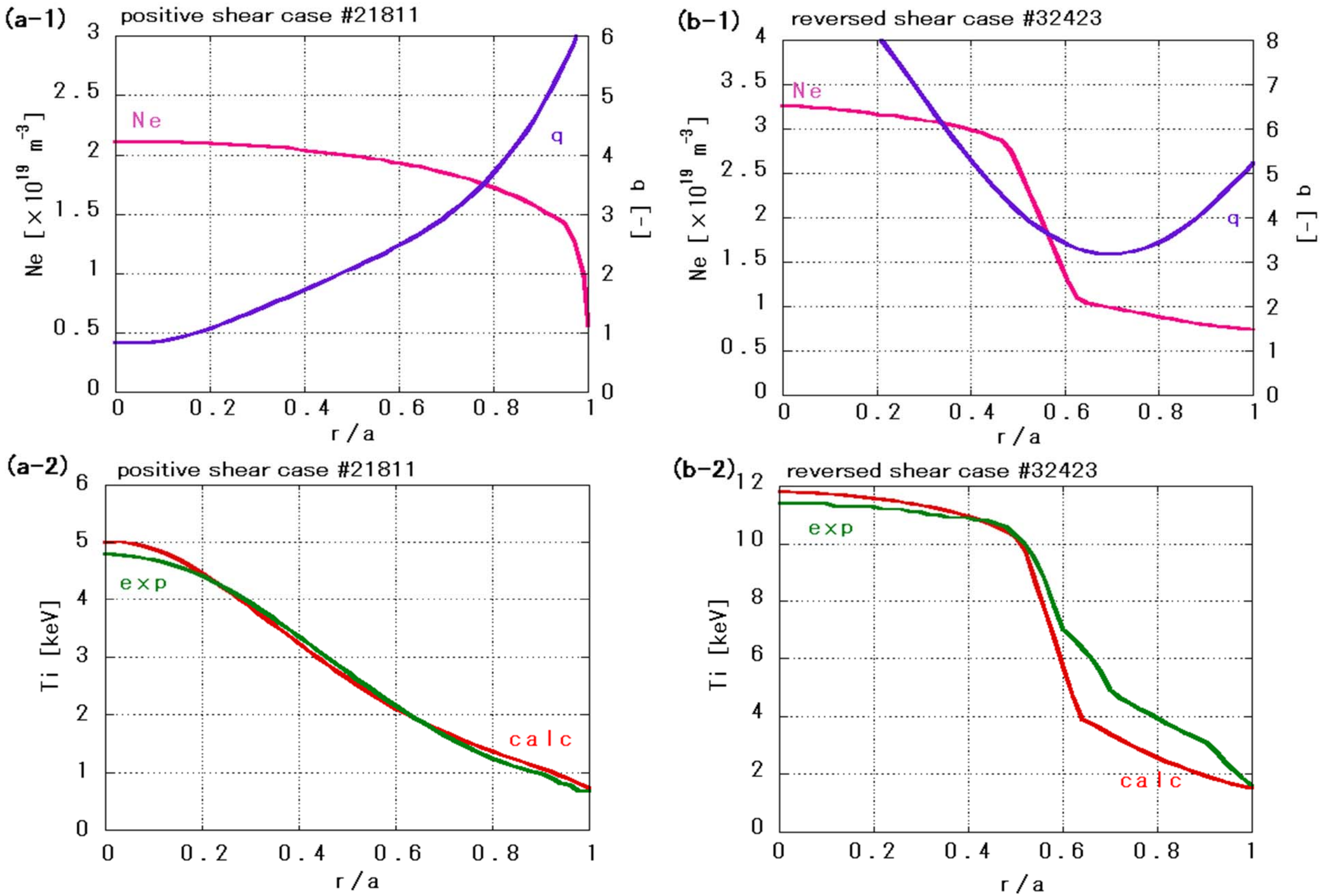
$$\chi_{anomalous} = \alpha_1 \times \chi_{GyroBohm} + \alpha_2 \times \chi_{Bohm} \times F\left(\omega_{E\times B} / \gamma_{ITG}\right)$$

$$F\left(\frac{\omega_{E\times B}}{\gamma_{ITG}}\right) = \frac{1}{1 + \left(\omega_{E\times B} / \gamma_{ITG}\right)^{\gamma}}$$

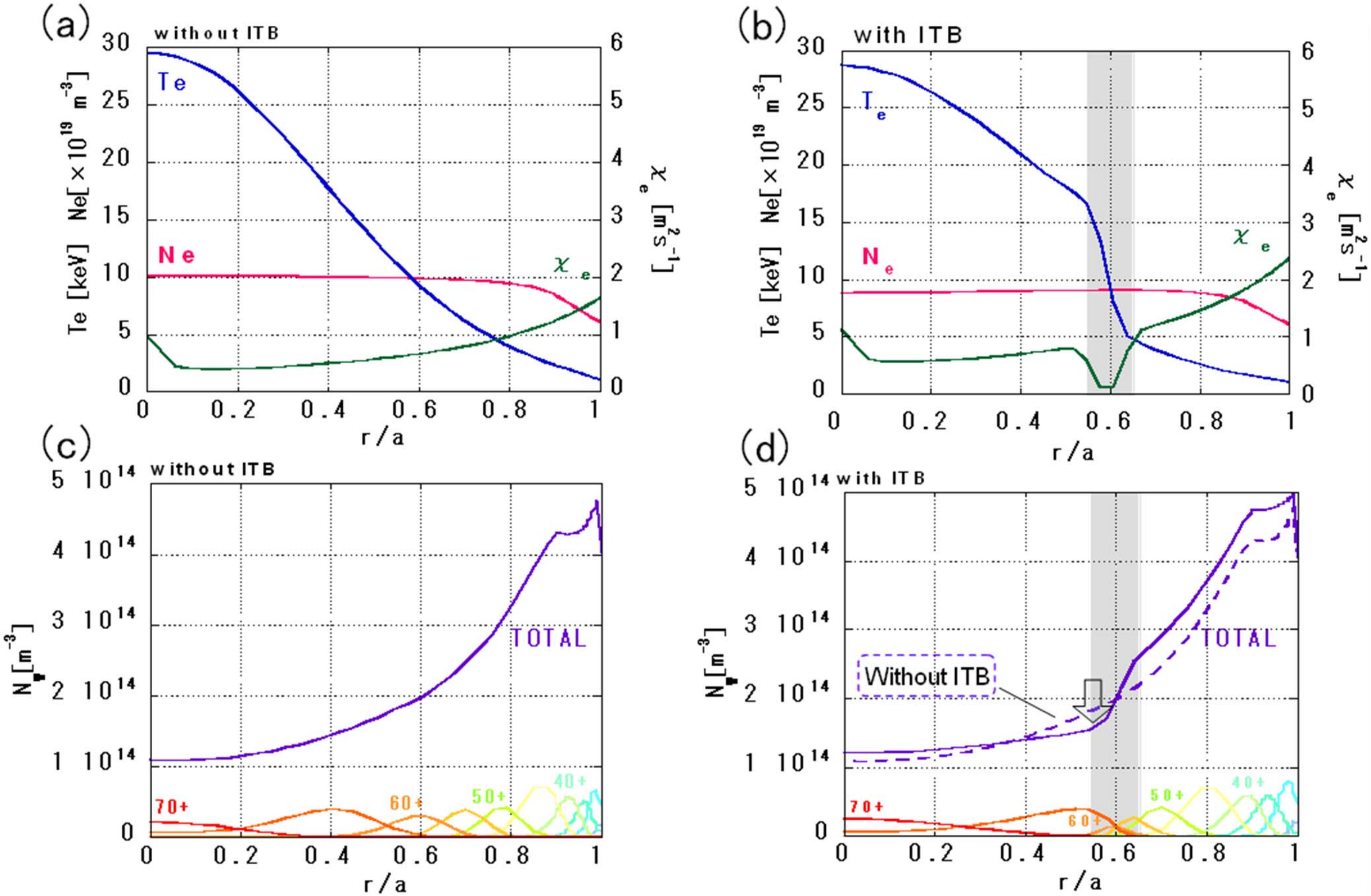
- E × B shearing rate : $\omega_{E\times B} \cong \left| \frac{RB_\theta}{B_\phi} \frac{d}{dr} \left(\frac{E_r}{RB_\theta} \right) \right|$
- ITG linear growth rate: $\gamma_{ITG} = \frac{(\eta_i - 2/3)^{1/2} |s| c_i}{qR}$ $\quad s \equiv \frac{r}{q} \frac{dq}{dr}$

Coefficients are determined using typical experimental data of JT-60U ITB data and LHD e-ITB operations.

Transport model cheked by JT-60U data

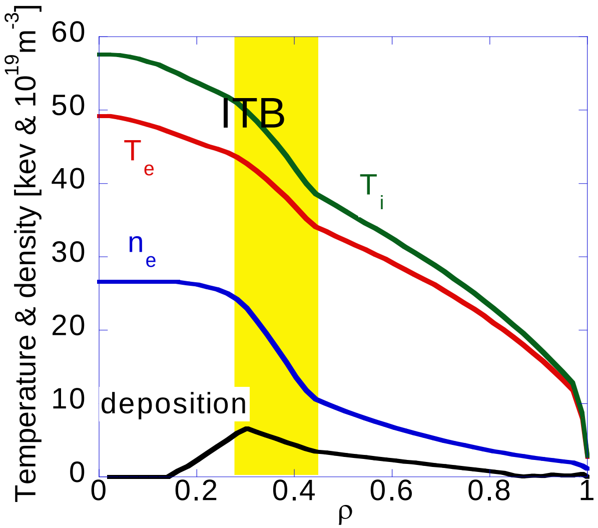


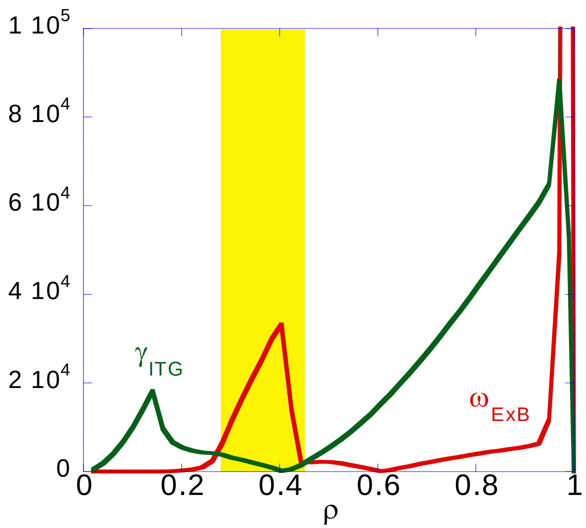
Tungsten Transport without and with ITB



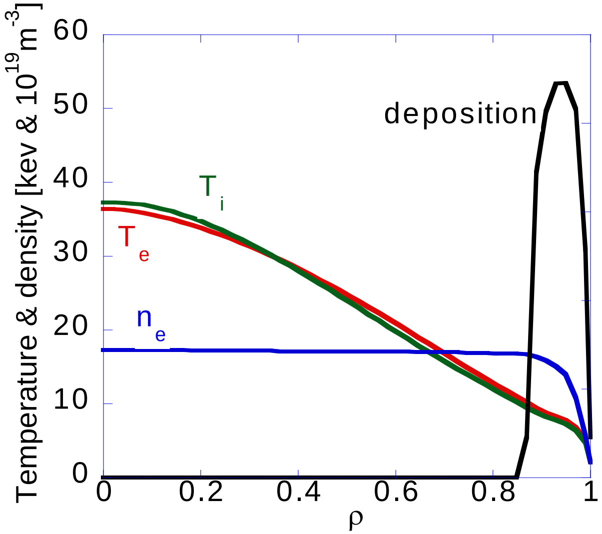
ITB Formation by Pellet Injection

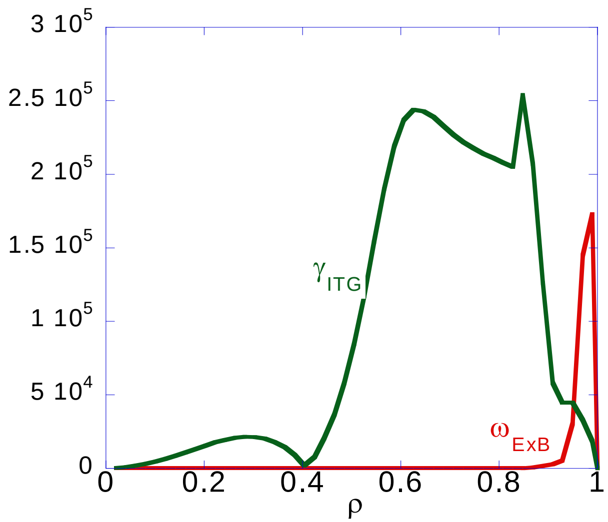
HFS Pellet Injection with ITB



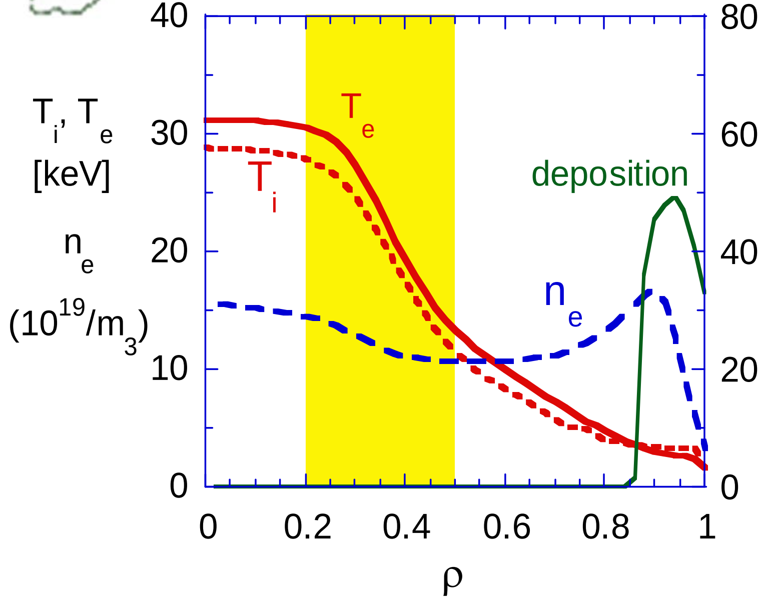


LFS Pellet Injection Without ITB

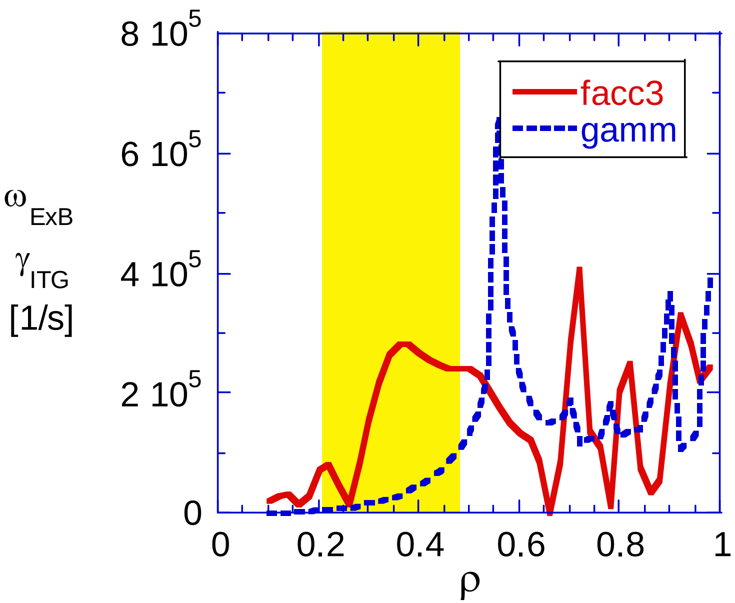


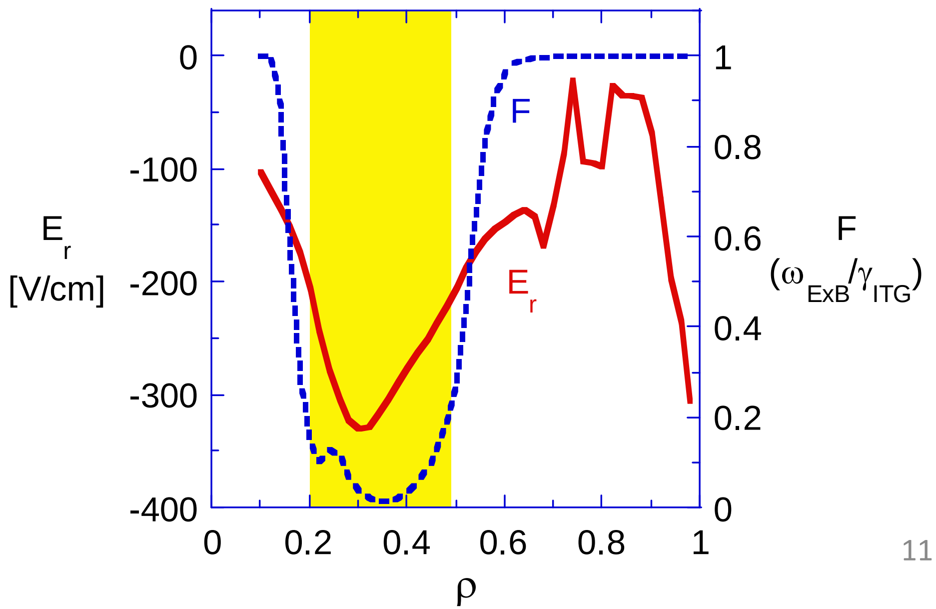


ITB formation in Helical Reactor HR-1



Ambipolar radial electric field can form ITB

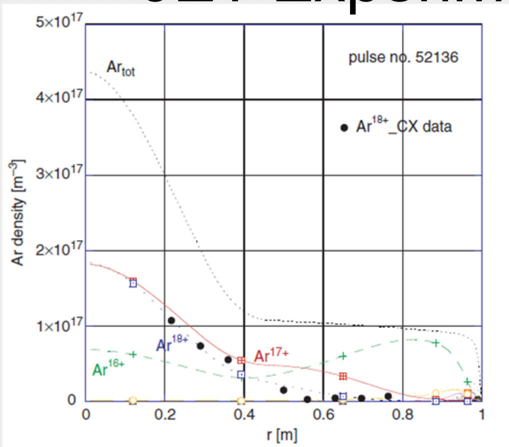


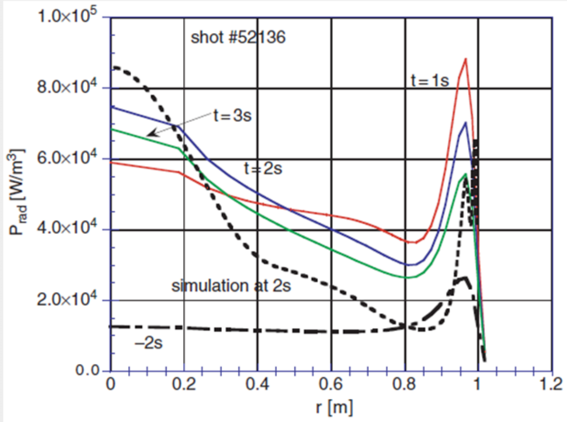


4. Impurity Injection and Edge Control

JET Experiment

#52136





Reference

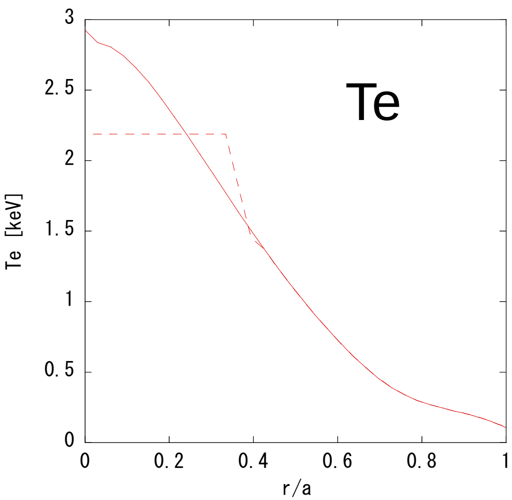
[1] M.E. Puiatti., et al., Plasma Phys. Control. Fusion 44 (2002) 1863
[2] M.E. puiatti., et al., Plasma Phys. Control. Fusion 45 (2003) 2011

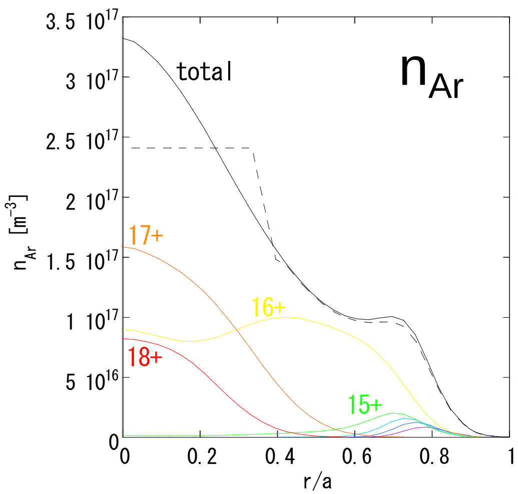
Low triangularity

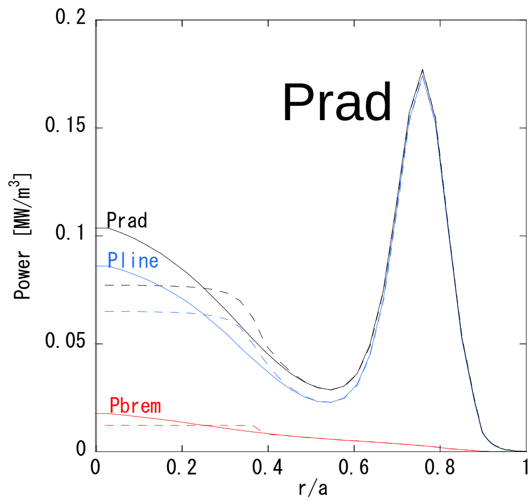
NBI 12MW

Argon seeded ELMy H-mode discharge

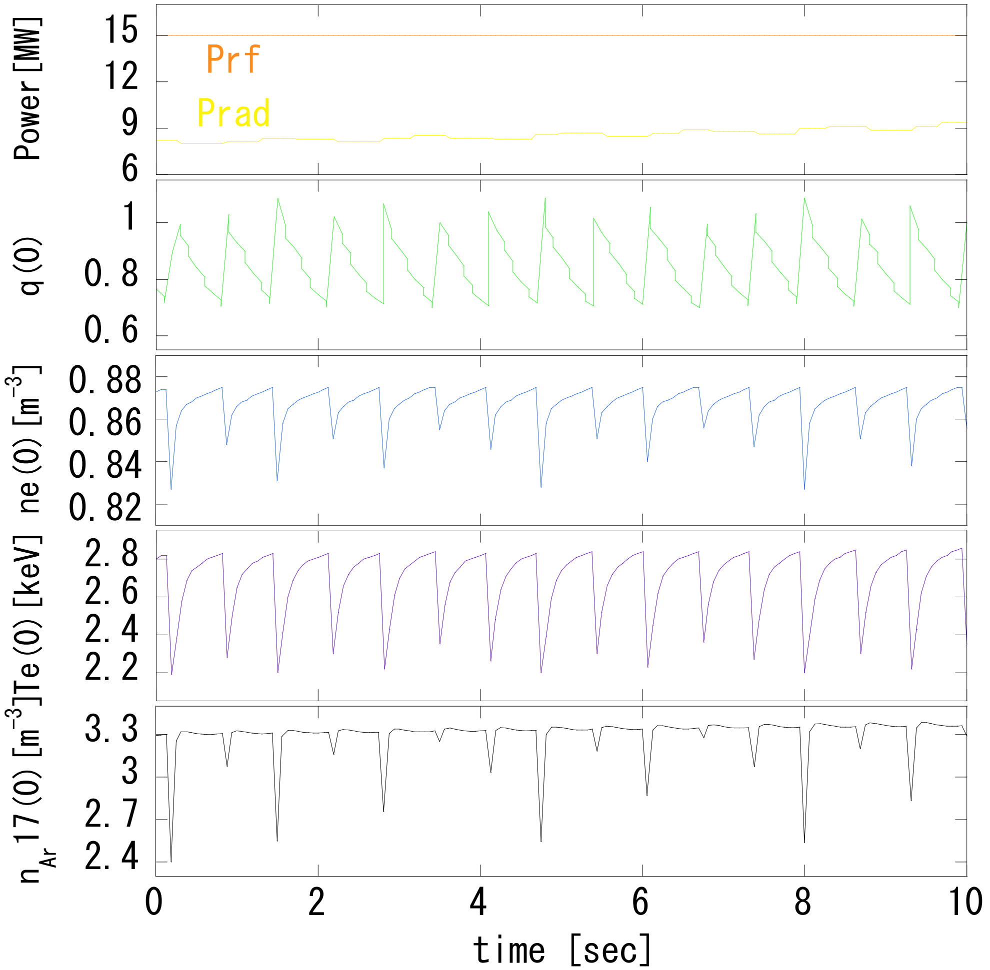
TOTAL code simulation with Sawteeth







Simulation for a JET Sawtooth

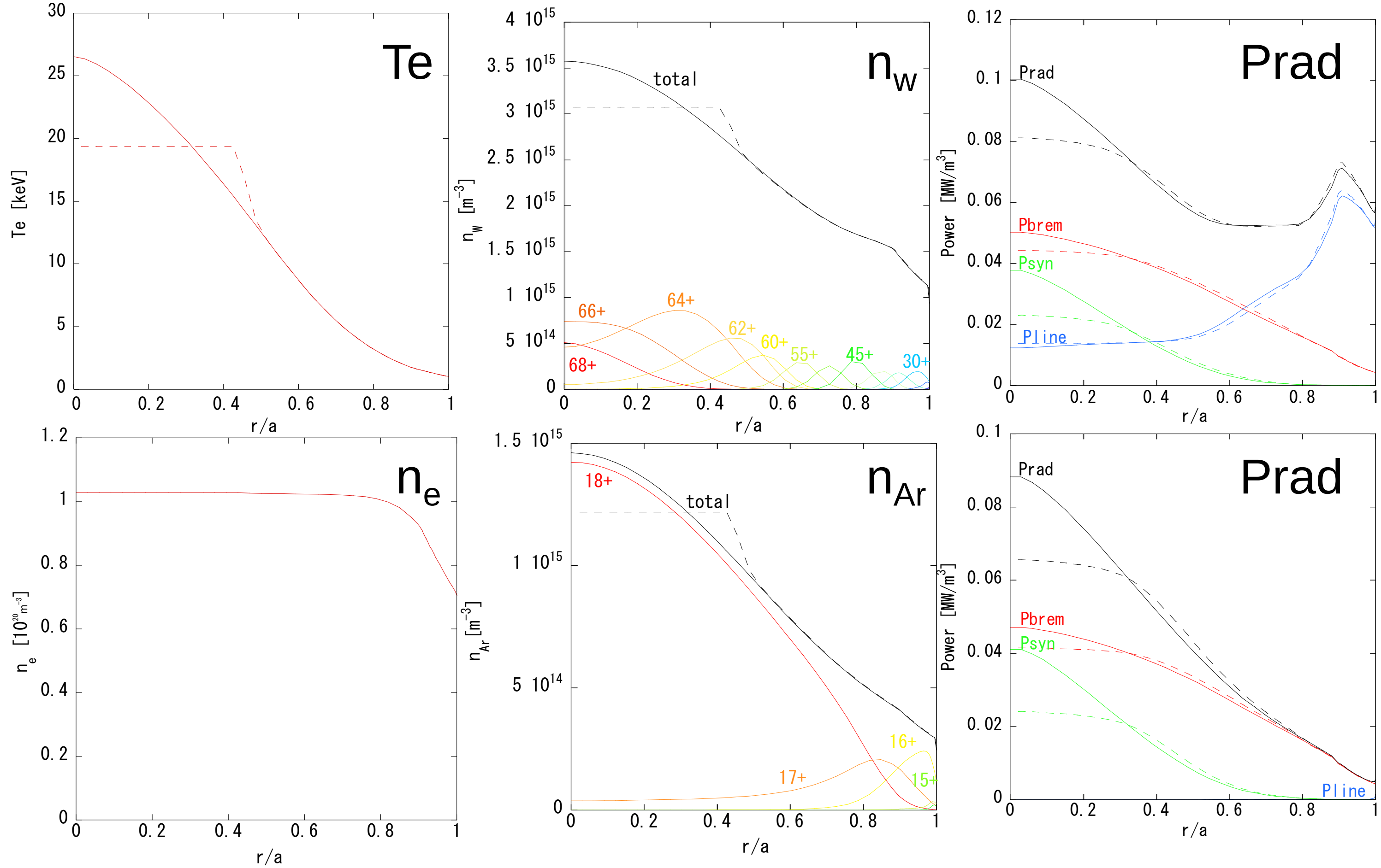


$$\tau_{saw} \sim 0.65[\text{sec}]$$

$$n_{Ar,s} = 7.0 \times 10^{17} / m^3$$

Radial profile before (solid curve) and after (dashed curve) a sawtooth crash.

ITER

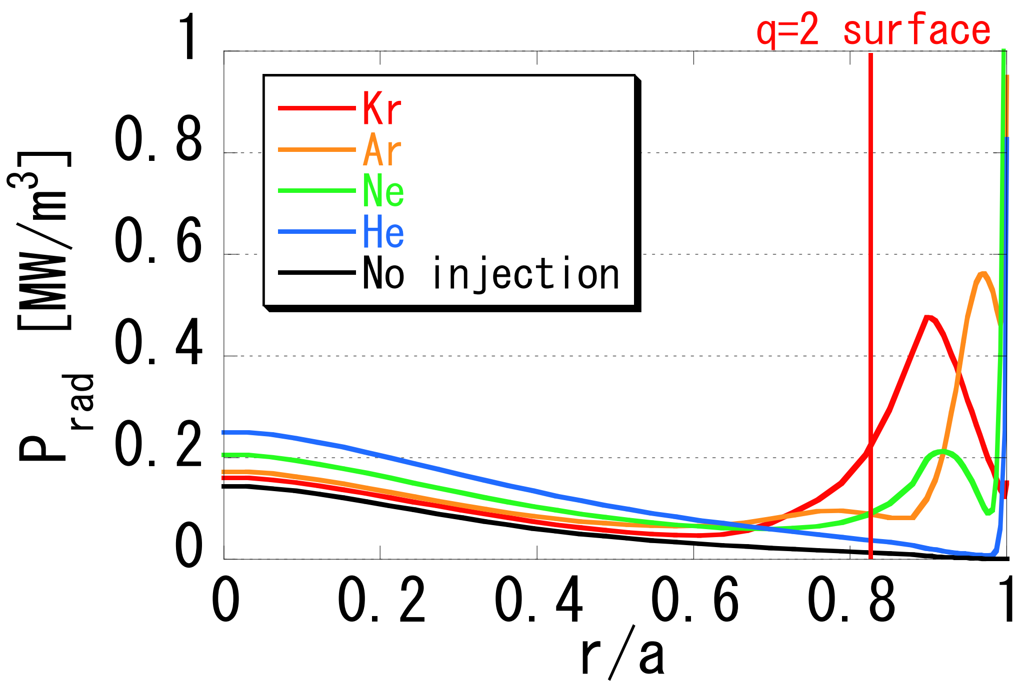


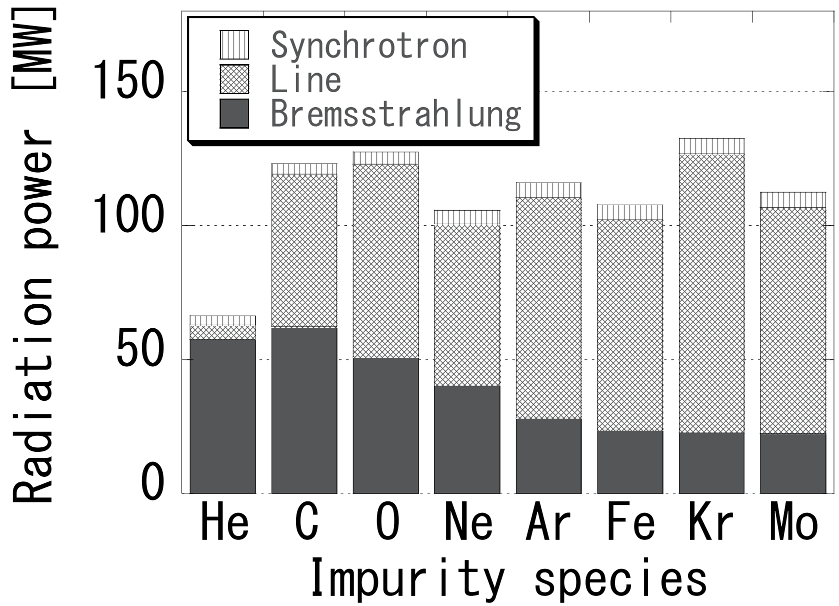
Maximum impurity concentration at the reference ITER inductive scenario based on the ELMy H-mode regime

$$P'_\alpha - P_\alpha \le P_\alpha \cdot 5\%$$

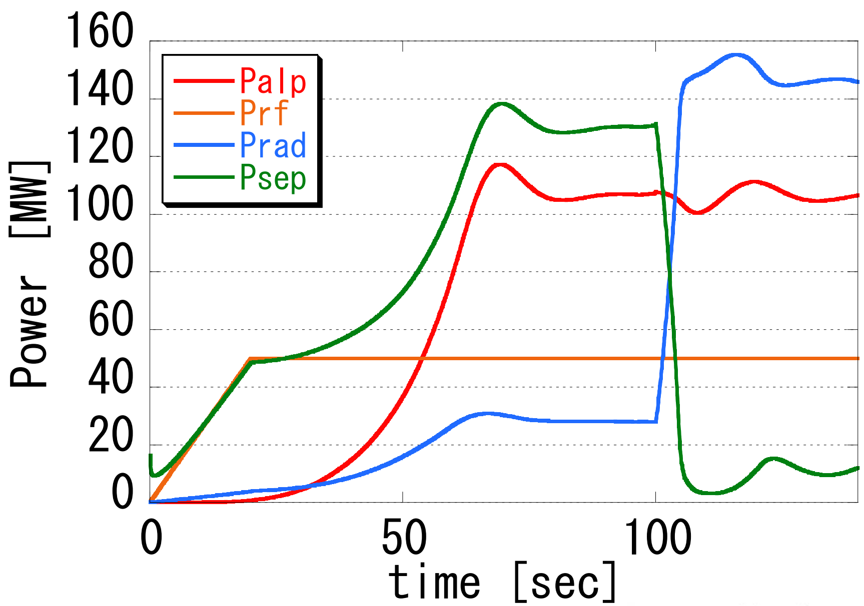
$$\overline{P}_{fus} \ge 10\,\overline{P}_{RF}$$

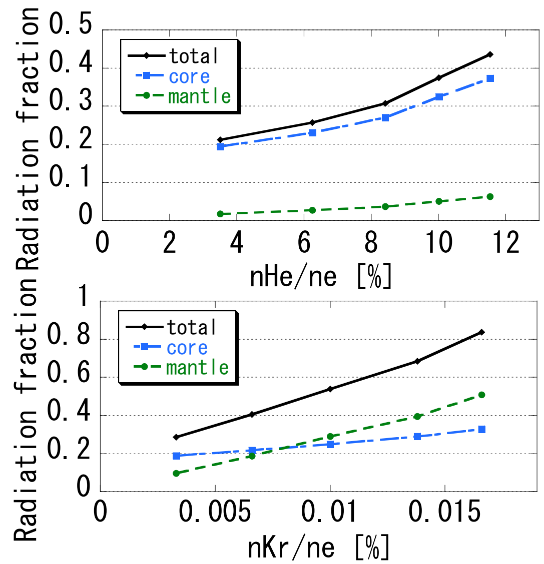
$$P_{sep} \ge P_{H\to L}$$

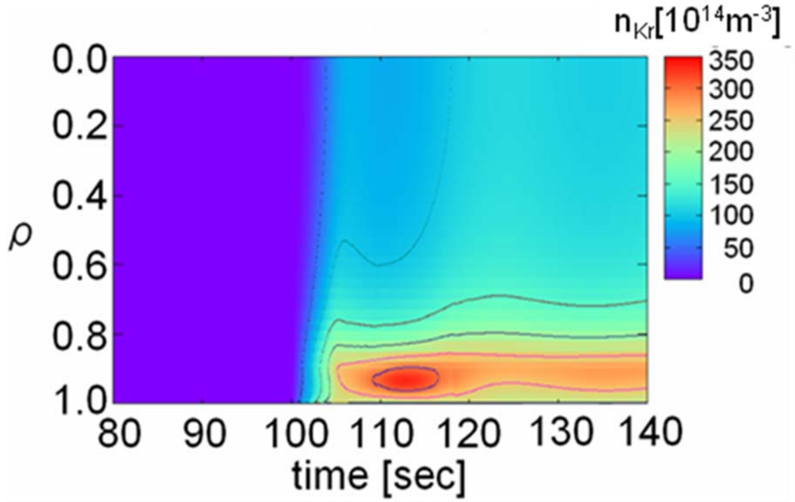


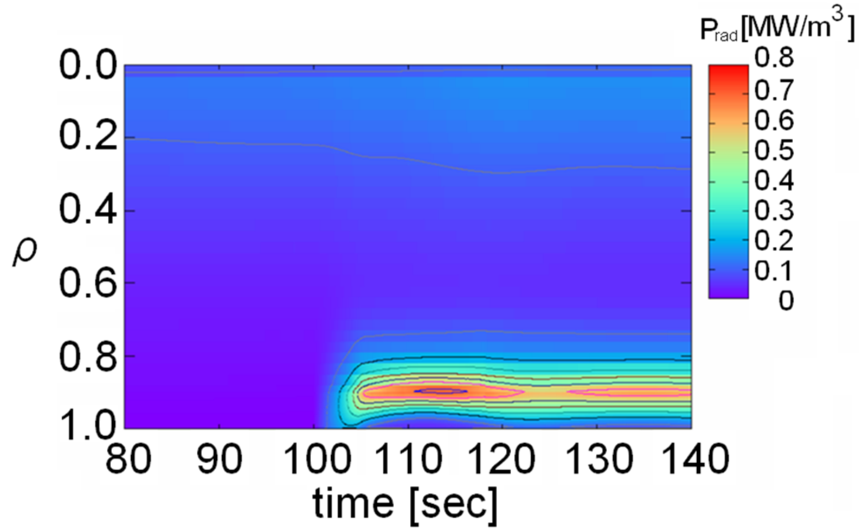


Radiative Mantle Formation by Kr Injection









5. NTM Evolution and ECCD Stabilization

Model: Modified Rutherford Equation

$$\frac{dW}{dt} = \Gamma_{\Delta'} + \Gamma_{BS} + \Gamma_{GGJ} + \Gamma_{pol} + \Gamma_{EC} + \Gamma_{HF}$$

$$\Gamma_{\Delta'} = k_1 \frac{\eta}{\mu_0} \Delta'(W) \left\langle |\nabla \rho|^2 \right\rangle$$

$$\Gamma_{BS} = k_2 \eta L_q j_{BS} \left\langle \frac{|\nabla \rho|}{B_p} \right\rangle \frac{W}{W^2 + W_d^2}$$

$$\Gamma_{GGJ} = -k_3 \frac{\eta}{\mu_0} \varepsilon_s^2 \beta_{ps} \frac{L_q^2}{\rho_s L_p} \left(1 - \frac{1}{q_s^2} \right) \left\langle |\nabla \rho|^2 \right\rangle \frac{1}{\sqrt{W^2 + 0.2 W_d^2}}$$

$$\Gamma_{pol} = -k_4 \frac{\eta}{\mu_0} g(\varepsilon_s, \nu_i) \beta_{ps} \left(\frac{\rho_{pi} L_q}{L_p} \right)^2 \left\langle |\nabla \rho|^2 \right\rangle \frac{1}{W^3}$$

$$\Gamma_{EC} = -k_5 \eta \frac{L_q}{\rho_s} \left\langle \frac{|\nabla \rho|}{B_p} \right\rangle f \eta_{EC} \frac{I_{EC}}{a^2} \frac{1}{W^2}$$

k_1	1.0
k_2	10.0
k_3	1.0
k_4	1.0
k_5	5.0

Resonant HF

$$\Gamma_{HF} = \frac{2m}{r_s} \left(\frac{W_{HF}}{W} \right)^2 \cos\phi$$

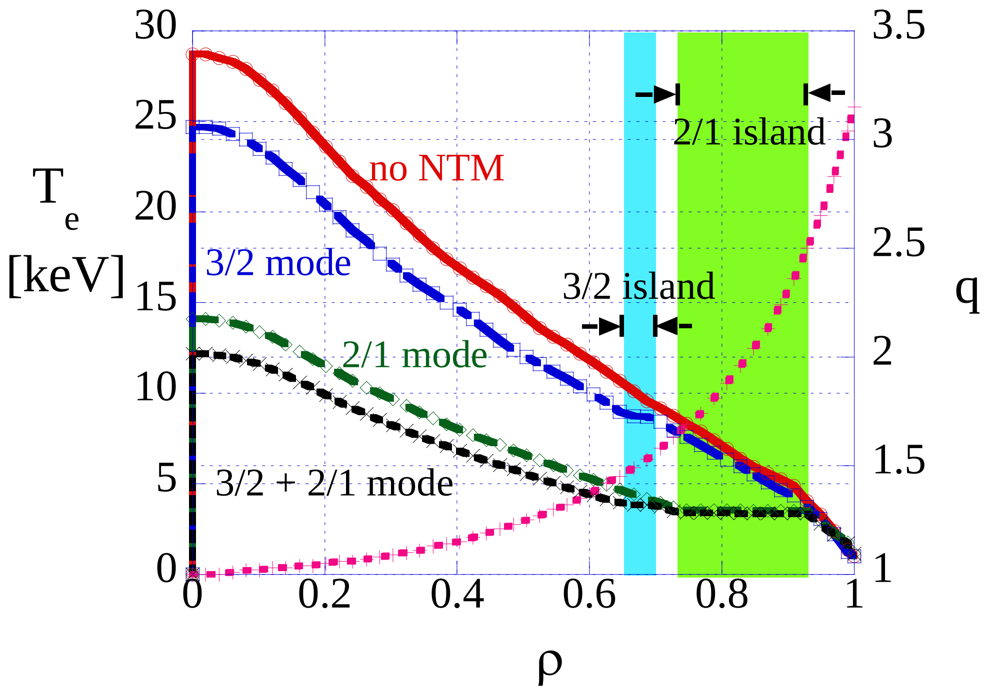
Non-resonant HF

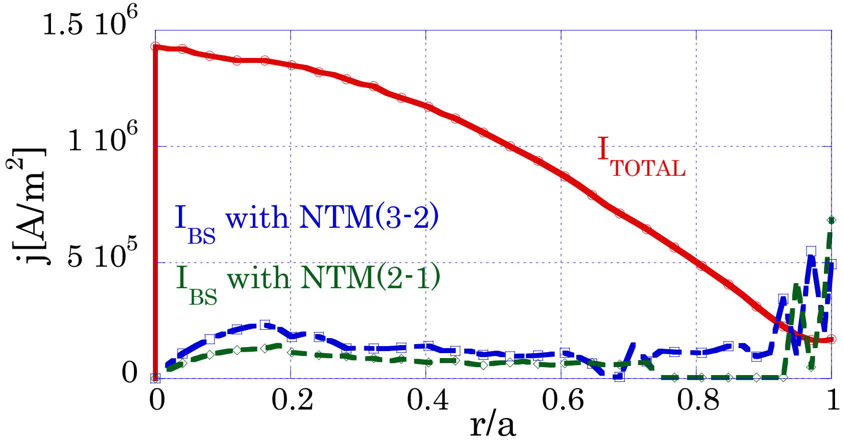
$$W_d \propto \left(\frac{\chi_\perp}{\chi_\parallel} \right)^4 \rightarrow \left(\frac{\chi_\perp}{\chi_\parallel} + \frac{b_r^2}{4} \right)^4$$

Q.Yu et al., PRL 85(2000)2949

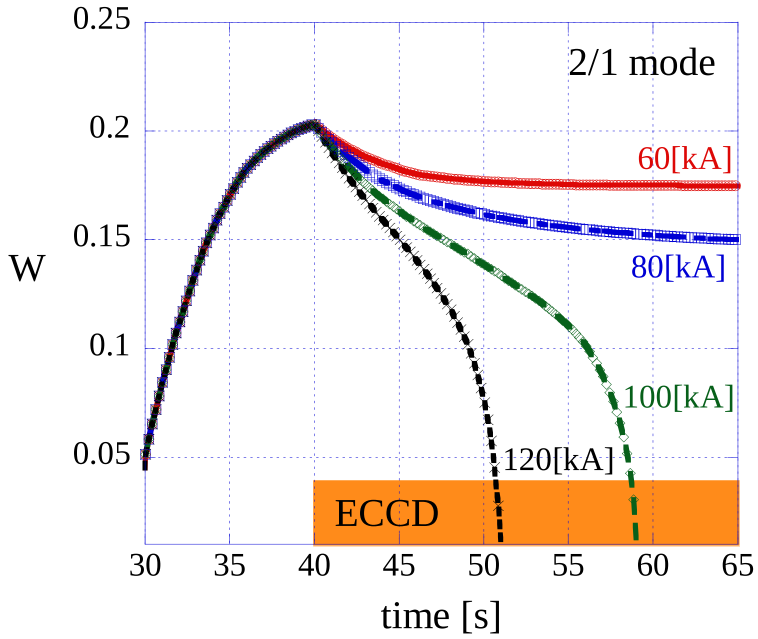
NTM analysis of an ITER Plasma without external helical field

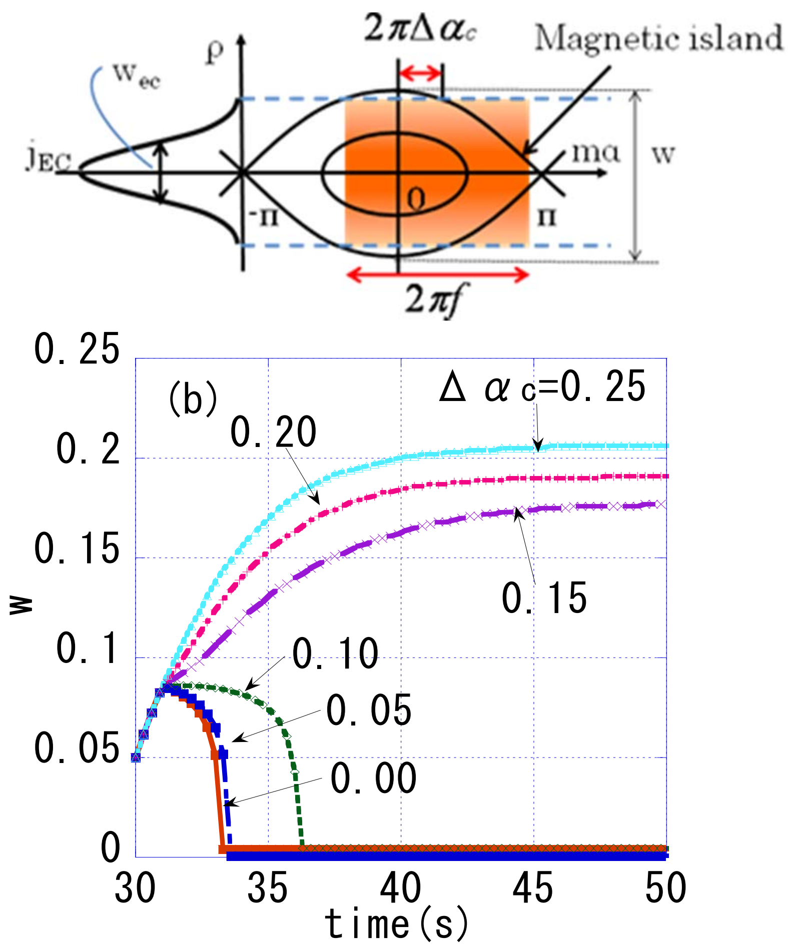
ITER (Ip=15MA)





ECCD Stabilization against NTM
In ITER Plasma

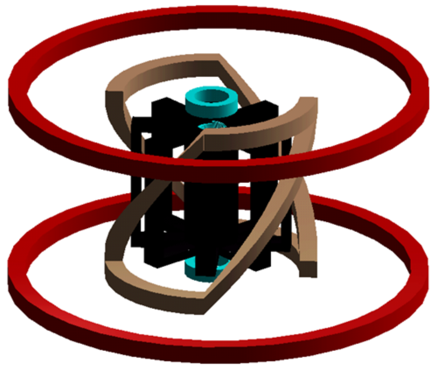




Application of External Helical Field

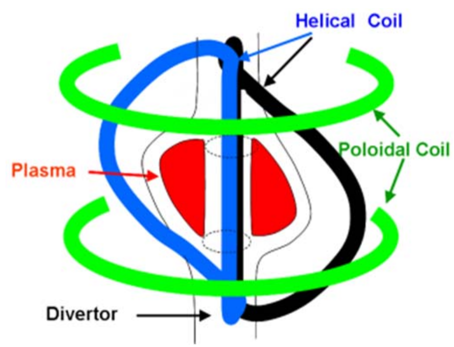
Old experiments on current carrying stellarator
disruption-free (without BS current)

(1) Error Field Modification ($B_{HF}/B \sim 10^{-4\sim-3}$)
resonant field feedback (high frequency)
resonant magnetic breaking (low frequency)

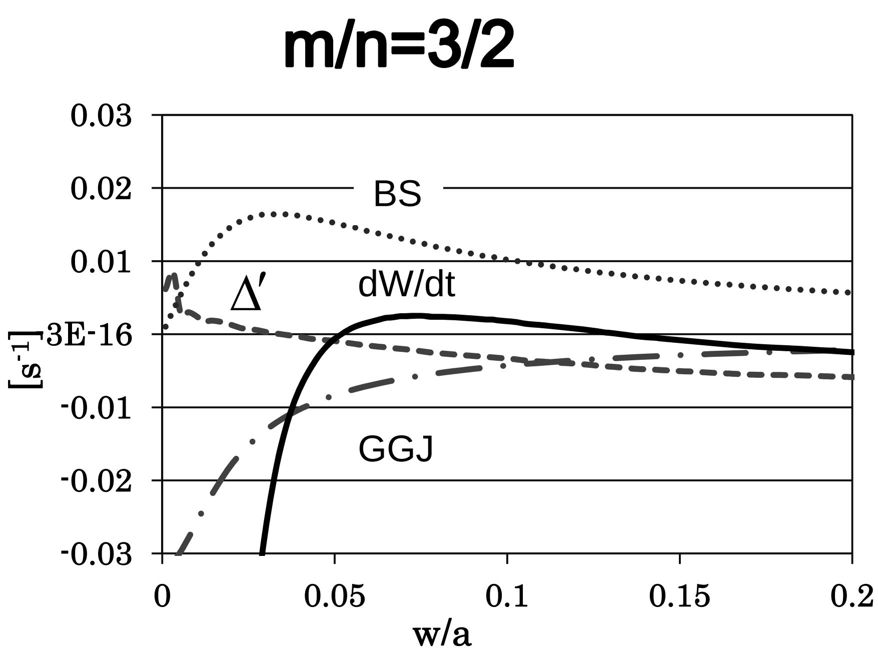


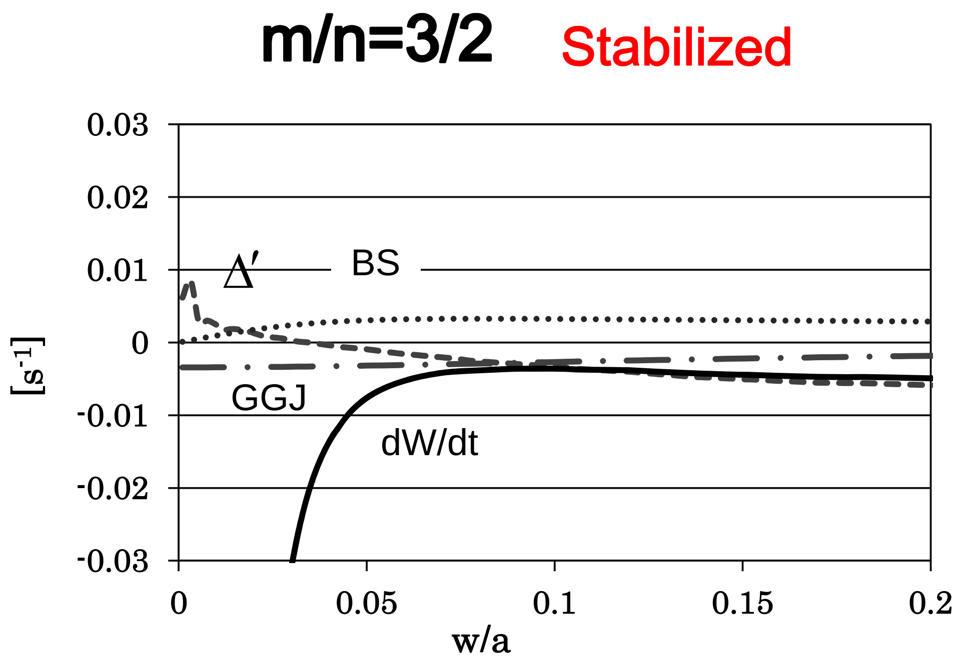
(2) Helical Field-Assisted ($B_{HF}/B \sim 10^{-2\sim-1}$)
static non-resonant application
➔ mode locked ? ➔ disruption ?

(3) Tokamak-Stellarator Hybrid ($B_{HF}/B \sim 1$)
static non-resonant application
➔ disruption-free ?



Non-Resonant Helical Field Application





Without Helical Field

With Helical Field

$B_r/B_0 \sim 10^{-3}$

6. Summary (1/2)

(1) 1.5-D tokamak code and 2.0-D helical code have been developed for predictive simulation and experimental analysis related to Transport and MHD effects.

(2) ITB can be formed by the deep penetration of HFS pellet injection in tokamaks. The shallow pellet penetration of low-field-side injection did not lead to the ITB formation in the present model.

(3) Sawtooth oscillation effects on ITER impurity transport has been carried out based on a JET simulation model, and 20% radiation reduction was suggested in ITER.

6. Summary (2/2)

(4) Low-z impurity, like He, cannot form radiative mantle, and causes large bremsstrahlung radiation loss in the core. About 84% (core:33% / mantle:51%) of input power is radiated inside the LCFS by Kr impurity seeding without inducing any deleterious change.

(4) NTM excitation and control have been simulated using modified Rutherford equation. The appearance of m=2/n=1 NTM leads to the 20 % reduction in the central temperature in ITER-like reactors. The m/n=3/2 NTM can be stabilized by non-resonant helical field.