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Divertor Modeling with a Simple Core-SOL-Divertor Model

US-Japan Workshop on
Theory-Based Modeling and Integrated Simulation of Burning Plasma

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Outline

1. Introduction and Motivation
2. Simple Core-SOL-Divertor model
3. Comparison of C-S-D model with the B2-EIRENE results
4. Application to HT-7U operation space
5. Future plan (Application to ITER)
6. Summary

Introduction

One of the important issues toward the future device and the fusion power plant

Core Plasma Operation

H-mode, RS mode, ELM, current drive, etc.

Consistency

SOL-Divertor Plasma Operation

Detached condition, He exhaust
Impurity seed, MARFE, etc.

Precise analysis by a multi dimensional code is preferable.

In the ITER modeling, the fitting scaling laws for divertor plasma property are built by a 2D divertor transport code, and these are used as boundary conditions for the 1D core plasma analysis[1,2].

Demerit of the multi-dimension code.

A multi-dimensional transport code is generally massive, and requires divertor geometry and large calculation cost.

Motivation

To carry out efficiently precise and consistent analysis for the core and edge plasma operation by the multi dimensional code.

It is necessary and effective to understand qualitatively the overall features of the integrated core and edge plasma operation space.

A simple Core-SOL-Divertor model is supposed to be a useful tool to understand qualitatively the overall features of the plasma operational space.

Objectives

To develop a Core-SOL-divertor model (C-S-D model) to investigate overall and integrated feature of operation space for core and SOL-divertor plasmas operation.

Concept of the C-S-D model[3]

Core Plasma

0D core plasma model of ITER physics guidelines

Core parameter

- Heat flux across the separatrix
- Particle flux across the separatrix
- Particle source by recycling effect

Integrate

SOL-Divertor Plasma

Two-point model

SOL-divertor parameter

- Heat flux across the separatrix
- Upstream SOL density: n_s
- Recycling effect

Problem : How to derive the upstream SOL density n_s ?
How to consider the recycling effect ?

- solve the particle balance for the SOL-divertor region including neutral transport.

Core Plasma Model

0D plasma model based on ITER physics guidelines[4]

$$\frac{dW_{\mathrm{th}}}{dt} = -\frac{W_{\mathrm{th}}}{\tau_{\mathrm{E}}} + P_{\alpha} + P_{\mathrm{OH}} + P_{\mathrm{aux}} - P_{\mathrm{Brad}} - P_{\mathrm{sync}}$$

$$\frac{dn_j}{dt} = -\frac{n_j}{\tau_{\mathrm{p}j}} + S_{\mathrm{n}j}^{\mathrm{core}} \quad (j = \mathrm{e}, \mathrm{He})$$

- Charge neutrality condition.
- Scaling law of energy confinement time.
- Particle confinement time: $\tau_{\mathrm{P}j} = C_{\mathrm{P}j}\,\tau_{\mathrm{E}}$
- Each definition from ITER physics guidelines.

LH transition condition[5]

- When the total input power within the separatrix (P_{in}) becomes larger than LH threshold power (P_{thr}), L to H transition occurs.
- When the total input power becomes smaller than the half of the LH threshold power, H to L transition occurs.

$$P_{\mathrm{thr}} = 2.76 M^{-1} B_{\mathrm{t}}^{0.92} n_{20}^{0.77} R^{1.23} a^{0.76} \text{[6]}$$

$$P_{\mathrm{in}} = P_{\alpha} + P_{\mathrm{OH}} + P_{\mathrm{aux}} - P_{\mathrm{Brad}} - P_{\mathrm{sync}}$$

L to H transition case

$$P_{\mathrm{in}} \geq P_{\mathrm{thr}}$$

H to L transition case

$$P_{\mathrm{in}} \leq \frac{1}{2} P_{\mathrm{thr}}$$

SOL-Divertor Model

Two-point model[7]

- momentum balance in the SOL-divertor region

$$\left(1-f_{mom}^{div}\right)n_s T_s = \left(1+M_d^2\right)n_d T_d$$

- global energy balance in the SOL-divertor region

$$\frac{7}{2}\left(1-f_{imp}\right)L_s q_\perp = n_d M_d C_s\left(T_d\right)\left[\varepsilon+\left(\gamma'+M_d^2\right)T_d\right]$$

- radial energy transport in SOL region

$$\Delta = \frac{5}{2}\chi_\perp \frac{n_s T_s}{q_\perp}$$

- electron thermal transport along the field lines

$$L_d^2 q_\perp = \frac{4\kappa_0 \Delta}{49} T^{7/2}\left[1-\left(\frac{T_d}{T_s}\right)^{7/2}\right]$$

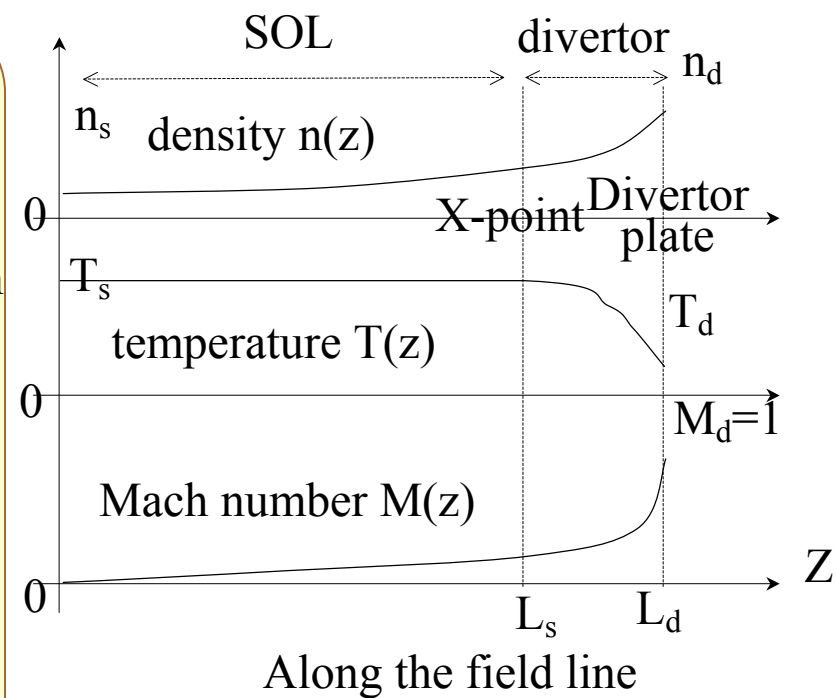


Fig. The basic features of density, temperature, and Mach number in the SOL-divertor region.

Neutral Transport Model

Assumption: **Neutral particle source rate at the divertor region is proportional to the particle flux to the divertor plate.**

1. All neutral particle source rate at the edge region N_n including gas puff term N_{puff}

$$N_n = n_d M_d C_s(T_d) 2\pi R \Delta_n \sin(\psi) + N_{puff}$$

2. Some neutral particles ionize in the divertor region by the fraction of f_{ion}^{div}.

3. Other neutral particles go into the core, SOL, and pumping regions by the fraction of f_{ion}^{core}, f_{ion}^{sol} and f_{ion}^{pump}, respectively.

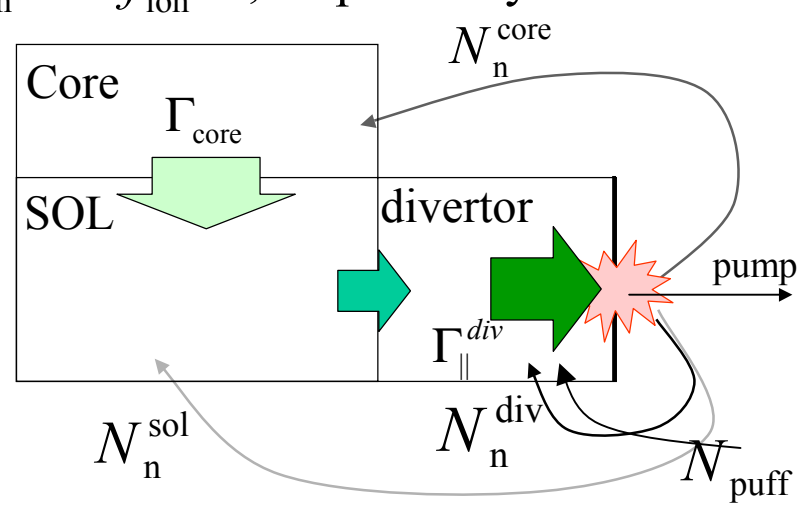


Fig. A simple model of the steady state particle balance.

Neutral Transport Model (cont.)

•ionization rate in the divertor region[8]

$$N_{\mathrm{n}}^{\mathrm{div}} = f_{\mathrm{ion}}^{\mathrm{div}} N_n$$

$$f_{ion}^{div} = 1 - \exp\left(-\frac{L_d \sin\psi}{\lambda_{ion}^{div}}\right)$$

$$\lambda_{ion}^{div} = \frac{v_n}{n_d \langle \sigma v \rangle}$$

•ionization rate in the Core region

$$N_{\mathrm{n}}^{\mathrm{core}} = f_{\mathrm{ion}}^{\mathrm{core}} \left(1 - f_{\mathrm{ion}}^{\mathrm{div}}\right) N_{\mathrm{n}}$$

$$f_{\mathrm{ion}}^{\mathrm{core}} = \frac{A_{\mathrm{core}}}{A_{\mathrm{core}} + A_{\mathrm{sol}} + A_{\mathrm{pump}}}$$

•ionization rate in the SOL region

$$N_{\mathrm{n}}^{\mathrm{SOL}} = f_{\mathrm{ion}}^{\mathrm{SOL}} \left(1 - f_{\mathrm{ion}}^{\mathrm{div}}\right) N_{\mathrm{n}}$$

$$f_{\mathrm{ion}}^{\mathrm{sol}} = \frac{A_{\mathrm{sol}}}{A_{\mathrm{core}} + A_{\mathrm{sol}} + A_{\mathrm{pump}}}$$

•pumping effect

$$N_{\mathrm{n}}^{\mathrm{pump}} = f_{\mathrm{ion}}^{\mathrm{pump}} \left(1 - f_{\mathrm{ion}}^{\mathrm{div}}\right) N_{\mathrm{n}}$$

$$f_{\mathrm{ion}}^{\mathrm{pump}} = \frac{A_{\mathrm{pump}}}{A_{\mathrm{core}} + A_{\mathrm{sol}} + A_{\mathrm{pump}}}$$

A_{core}, A_{sol}, and A_{pump} are effective area from the divertor region.
To specify these parameters more precisely, numerical analysis by multi-demensional Monte Calro nueutral transport code will be done in the future.

Particle balance of SOL-divertor region

Total particle flux to the divertor plate is equal to the sum of total flux from core plasma, particle source in both SOL and divertor region

$$\Gamma_{\mathrm{core}} S_{\mathrm{core}} + N_{\mathrm{n}}^{\mathrm{sol}} + N_{\mathrm{n}}^{\mathrm{div}} = \Gamma_{\parallel}^{\mathrm{div}} S_{\mathrm{div}}$$
$$= n_{\mathrm{d}} M_{\mathrm{d}} C_{\mathrm{s}}(T_{\mathrm{d}}) \sin(\psi) S_{\mathrm{div}}$$

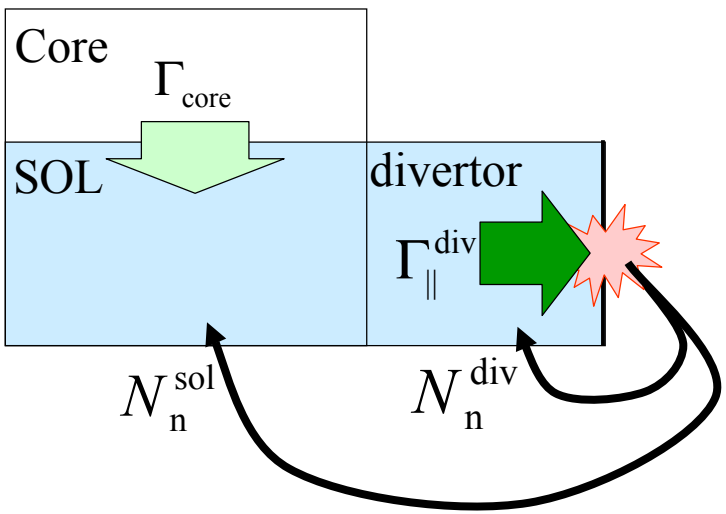


Fig. particle balance of the SOL-divertor region.

Comparison with B2-EIRENE

JT-60U simulation result for the attached state[9]

- We focus on the inner divertor.
- The fraction of the power entering inner SOL across the separatrix to the total power is P_{in}/P_{all} =0.34.
- The percentage of the total radiation power to the input power f_{imp} is about 30 %

	C-S-D model	B2-EIRENE
SOL density n_s [m^{-3}]	1.0×10^{19}	$\sim 1 \times 10^{19}$
SOL Temp. T_s [eV]	50.0	~55
Div density n_d [m^{-3}]	2.3×10^{19}	$\sim 2.4 \times 10^{19}$
Div Temp. T_d [eV]	12.3	~10

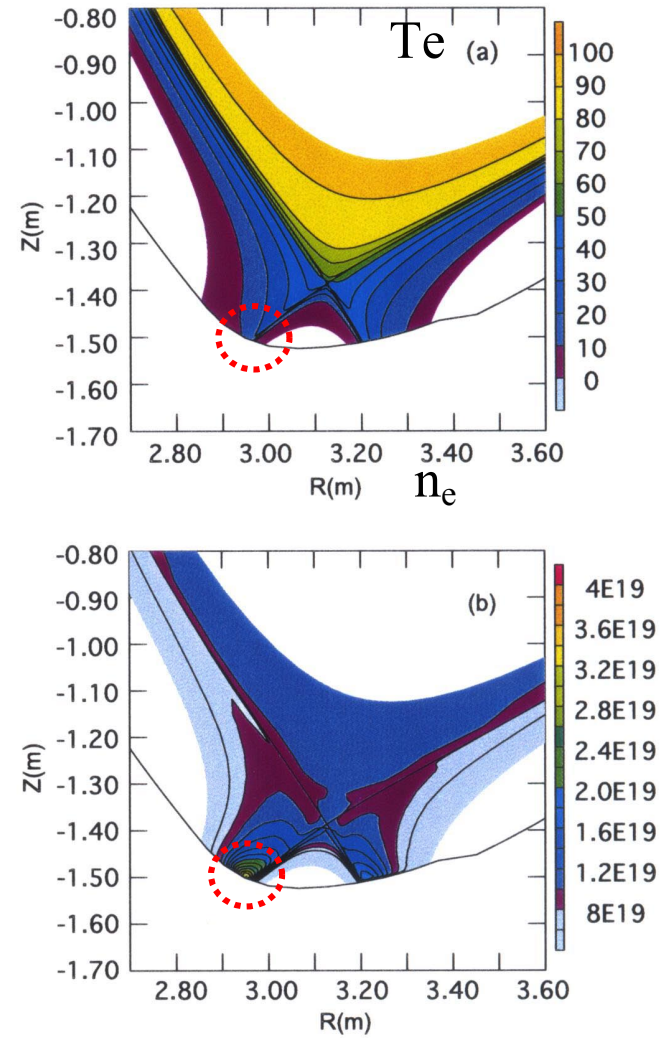
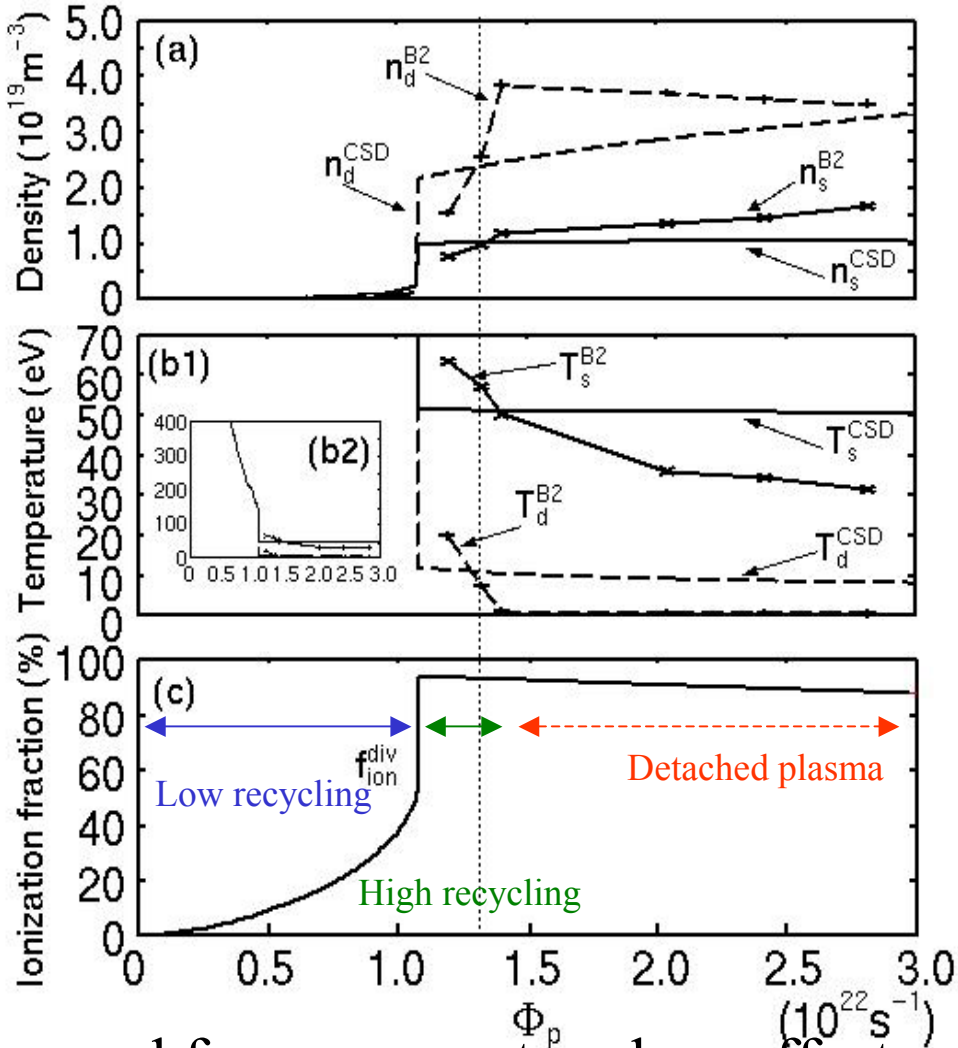


Fig T_e and n_e of B2-EIRENE

Comparison with B2-EIRENE(cont.)

Dependence on the particle flux from core plasma.

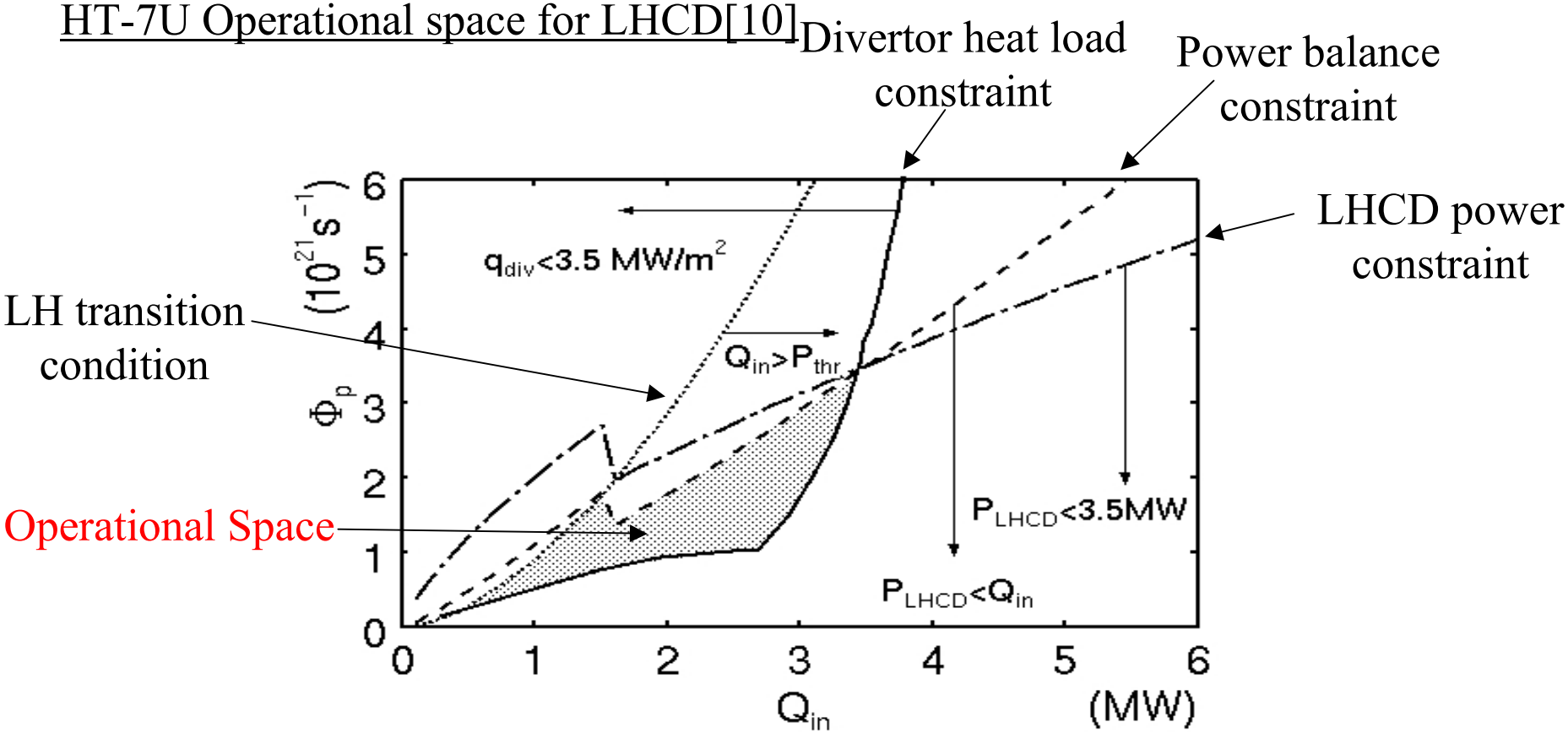
- The parameter dependence of the C-S-D model looks reasonable in comparison with B2-EIRENE
- At $\Phi p \sim 1.3 \times 10^{22}$ s^{-1}(where divertor densities of CSD and B2 are equal), C-S-D model reproduces other SOL-divertor parameters similar to B2-EIRENE.
- C-S-D model reproduce the transition from low to high recycling state



Difference after $\Phi_p \sim 1.5 \times 10^{22} s^{-1}$ is caused from momentum loss effect

Application to HT-7U Operation Space

HT-7U Operational space for LHCD[10]



- Upper boundary of Q_{in} is divertor heat load constraint
- Upper boundary of Φ_p is power balance constraint for low Q_{in}, LHCD power constraint for high Q_{in}
- Lower boundary of Φ_p is divertor heat flux constraint

Application to ITER LH Transition phase

- Plasma parameters at t=250 sec are almost the same as the reference parameters of ITER inductive operation scenario
- At t=100 sec, plasma parameters are also similar to the reference parameters of ITER.
- Density increases from t=95 sec.
- Auxiliary heating is added at t=100 sec.
- LH transition occurs at t=104 sec.

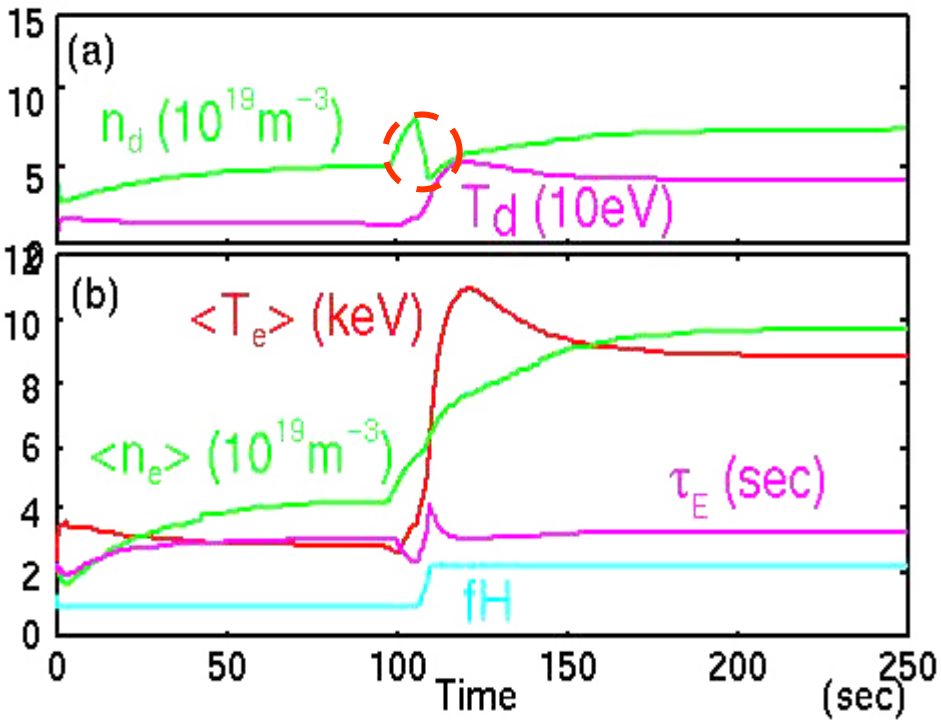


Fig. (a) Density and temperature, (b) core plasma parameter during the ITER LH transition phase.

- Just after LH transition, divertor temperarure increases
- Divertor deinsity oscillate according to this result.

This result implies that careful operation will be required during LH transition phase

Future Plan (Application to ITER)

Application to ITER LH transition phase, and evaluate the overall feature of divertor operation conditions for detached plasma.

1. Detached plasma modeling from the divertor density (n_d), temperature (T_d), neutral particl (Nn) condition.
   Comparison with the experimental recycling data.

2. Evaluate the operation guideline for the divertor plasma during LH transition.
   Operation condition e.g., gas puff, impurity seeding, for the alpha heating just after LH transition.

3. Effects of the divertor operation on the core plasma.
   consistency between the divertor operation (gas puff, impurity seeding) and LH transition condition
   →install C-S-D model into 1D plasma transport code.

Comparison with JT-60U Divertor Recycling DB1

- JT-60U Divertor Recycling Database (DRC-JT60U.DB.v1)[11]
- Comparison with neutral particle source and recycling effects

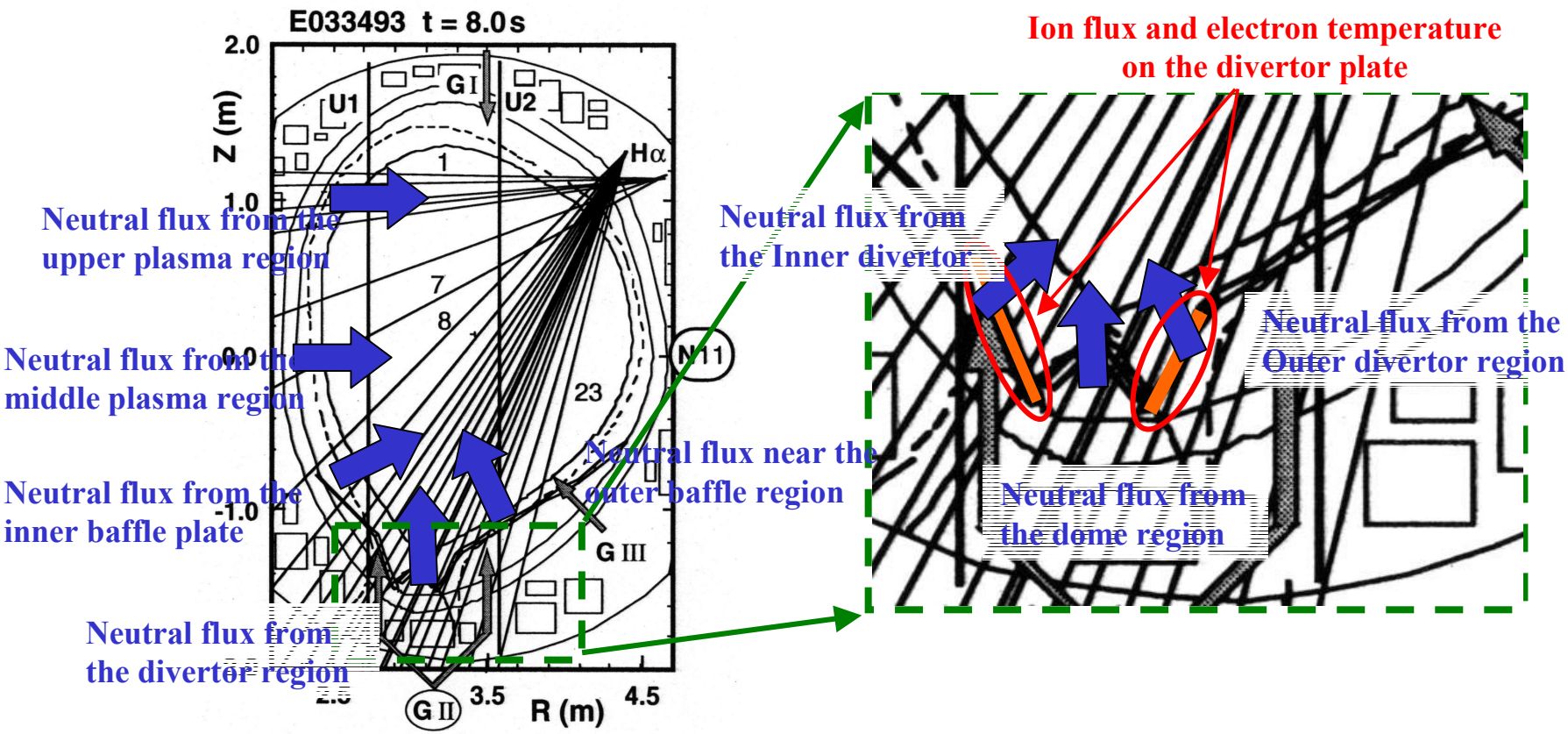
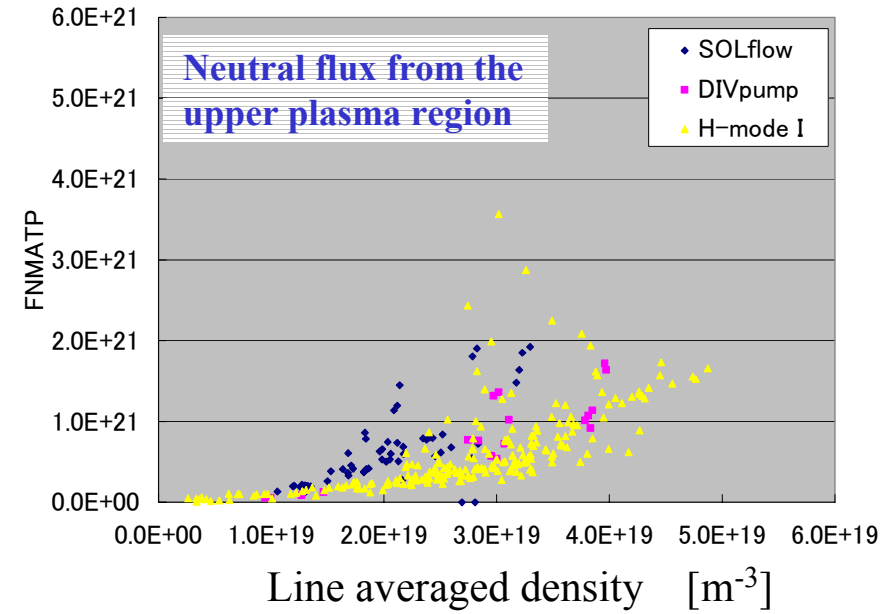
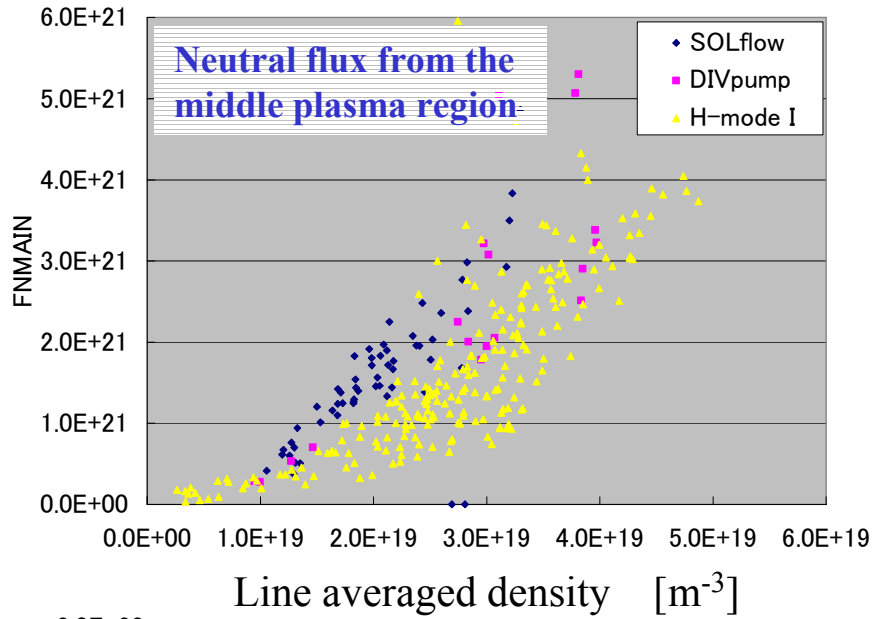
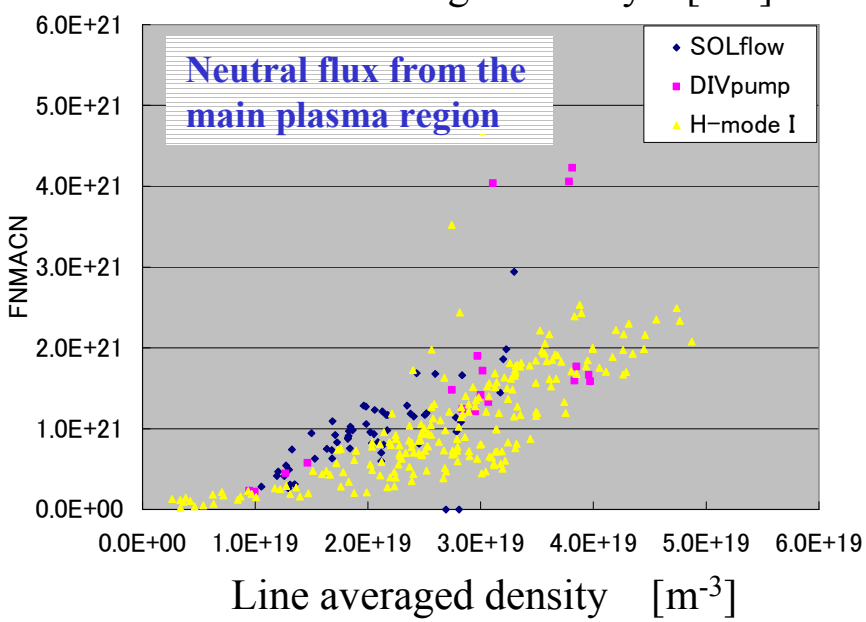


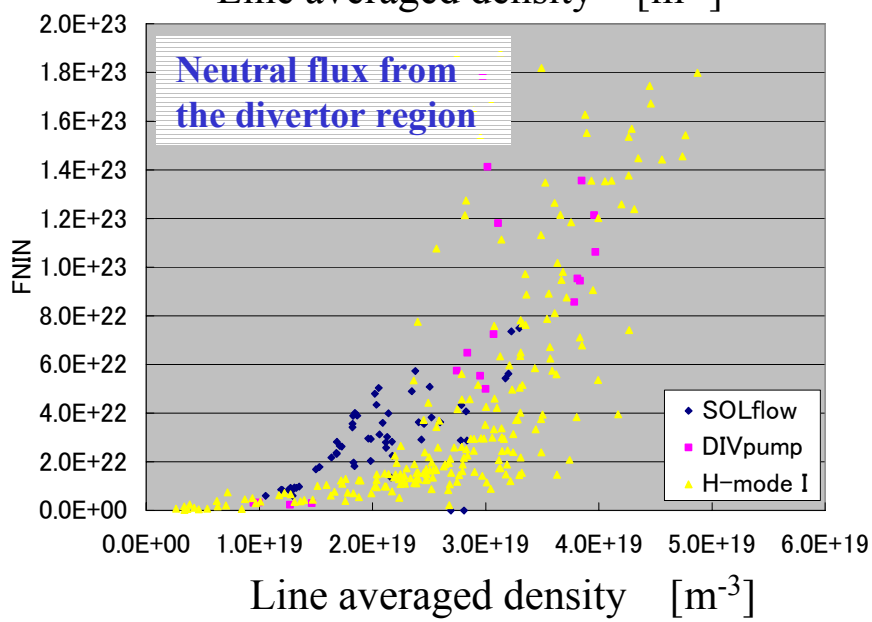
Fig. JT-60U Divertor Recycling Database (DRC-JT60U.DB.v1)

Outline of Divertor Recycling Database



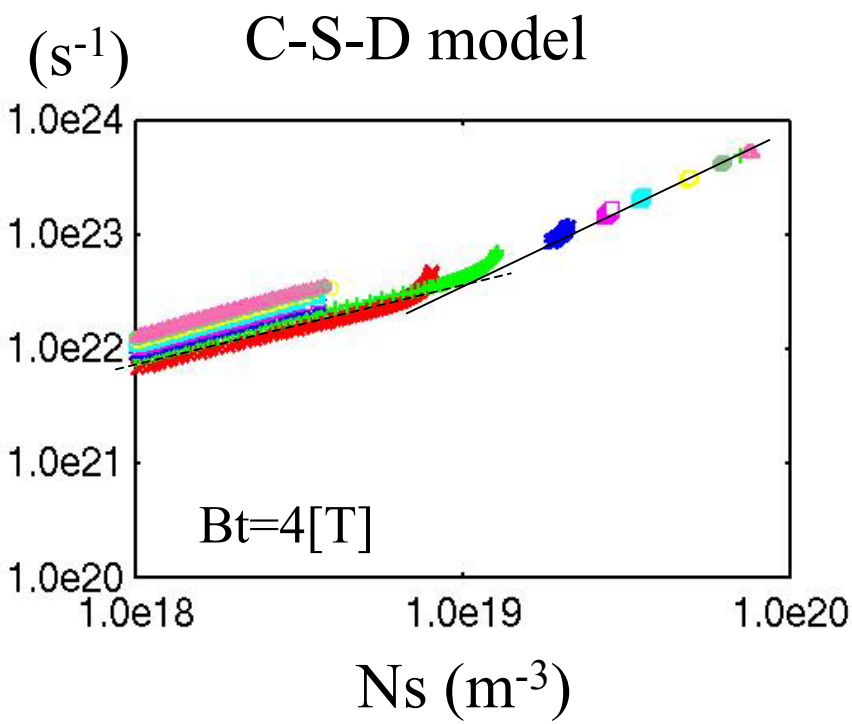


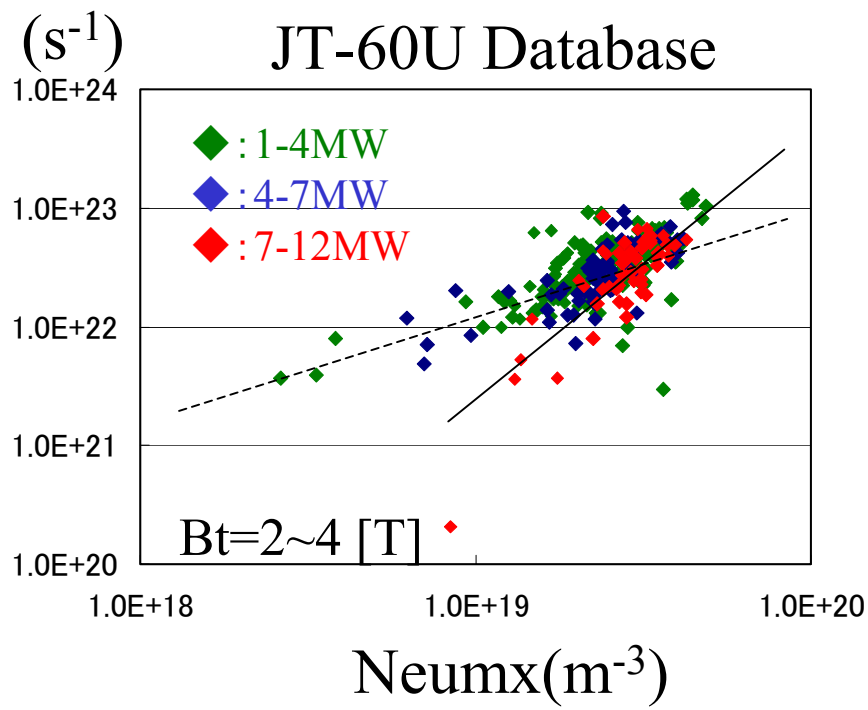




Comparison of ion flux to the divertor plate

- Power entering into SOL region : 0.5~4.0MW.
- Total particle flux into SOL region : Φp=1.0e20-1.0e23(s^{-1})
- Upstream SOL density（C-S-D model）、line averaged density（Database）
- The same order of ion flux to the divertor plate.

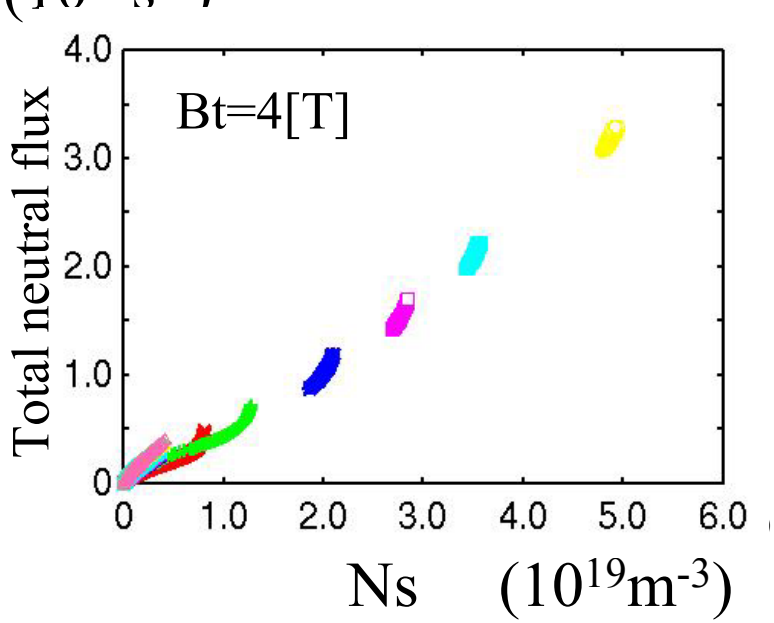




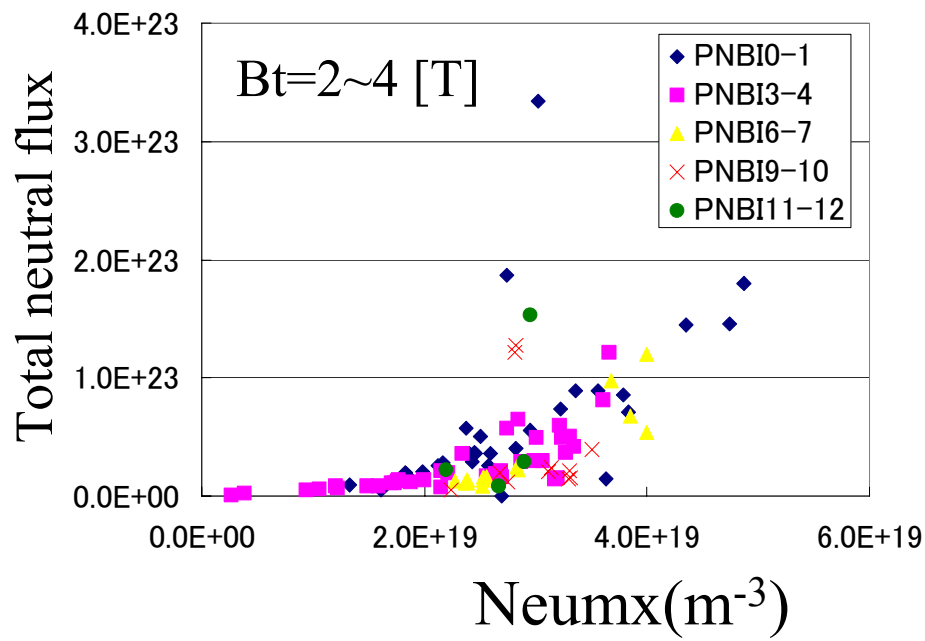
Comparison of neutral flux from the divertor

- Neutral flux from the inner side divertor region
- Neutral flux by C-S-D model is about twice of JT-60U database.

C-S-D model



JT-60U Database



Future Plan (Application to ITER)

Application to ITER LH transition phase, and evaluate the overall feature of divertor operation conditions for detached plasma.

1. Detached plasma modeling from the divertor density (n_d), temperature (T_d), neutral particl (Nn) condition.

   M.Sugihara, et al., "Modelling of transition from attached to detached state and self consistent calculations of He levels in ITER", J.Nucl. Mater. **241-243**(1997)299-304

2. Evaluate the operation guideline for the divertor plasma during LH transition.
   Operation condition e.g., gas puff, impurity seeding, for the alpha heating just after LH transition.

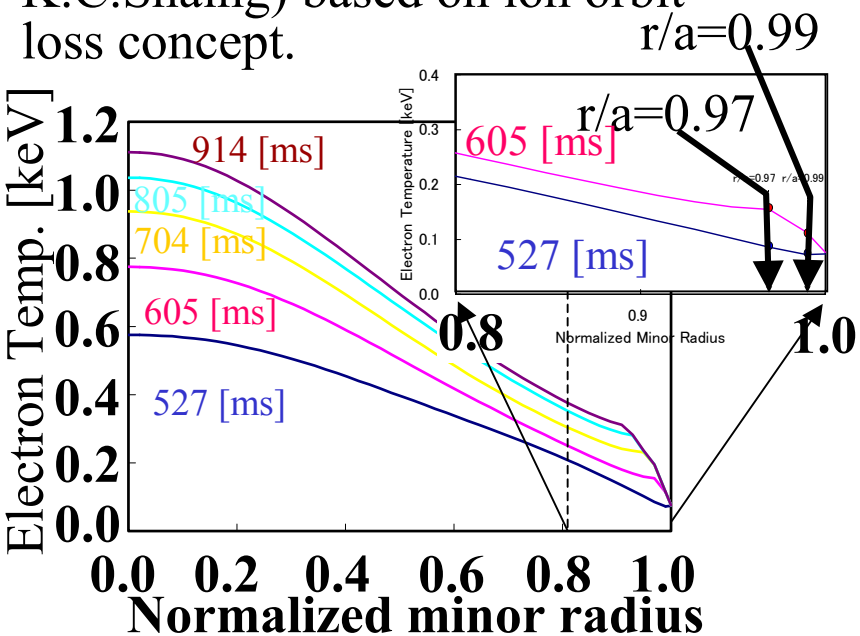
3. Effects of the divertor operation on the core plasma.
   consistency between the divertor operation (gas puff, impurity seeding) and LH transition condition
   →install C-S-D model into 1D plasma transport code.

CSD model

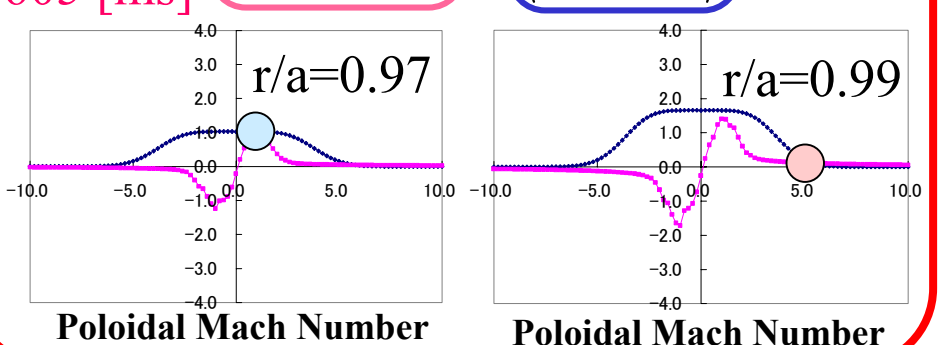
1D transport code

1D Transport code for LH transition

LH transition model(proposed by K.C.Shaing) based on ion orbit loss concept.

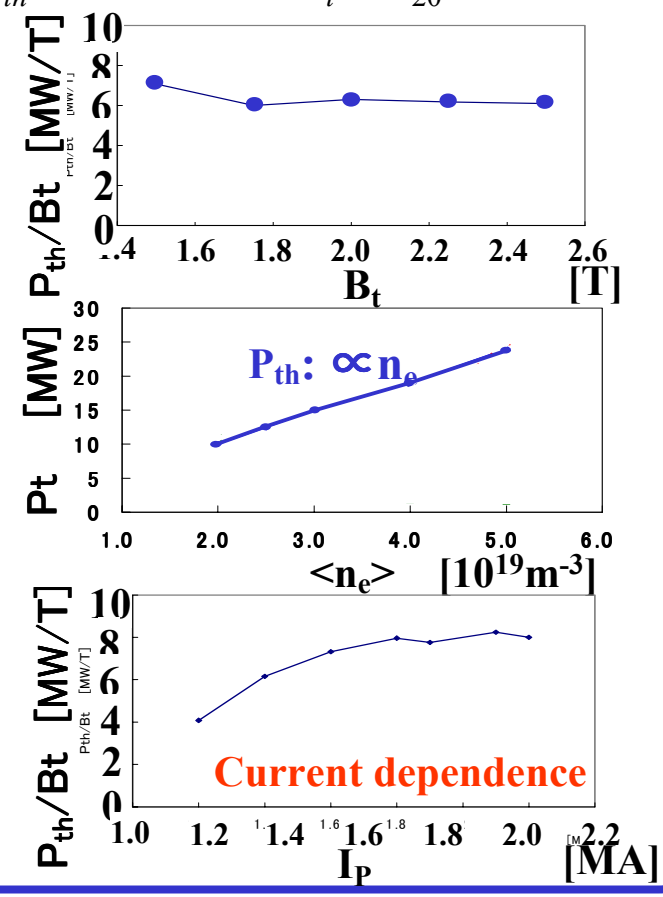


605 [ms] $\langle \mathbf{B}\cdot\nabla\cdot\Pi_i \rangle = \langle \mathbf{B}\cdot\mathbf{S}_{i,orb} \rangle$



Comparison of B_t and n_e depencence

$$P_{th}^{LH} = 2.67 M^{-1} B_t^{0.96} n_{20}^{0.77} R^{1.22} a^{0.76}$$



By using this trasnport code, how to analyze the consistency between core and edge will be examined.

→ Other LH transition model

Summary

- The C-S-D model has been developed to investigate overall and integrated features of core and edge plasma in tokamaks. The C-S-D model is qualitatively consistent with B2-EIRENE.
- By using the C-S-D model, the basic features of possible operational space have been studied for the LHCD steady-state operation. the C-S-D model is considered as a useful tool to understand qualitatively the overall features of the operation space
- Comparison with JT-60U recycling database is carried out, and the neutral flux by the CSD model is almost the same order.
- The consistency between core and edge during LH transition of ITER will be examined in the near future by using C-S-D model and 1D transport code.

Reference

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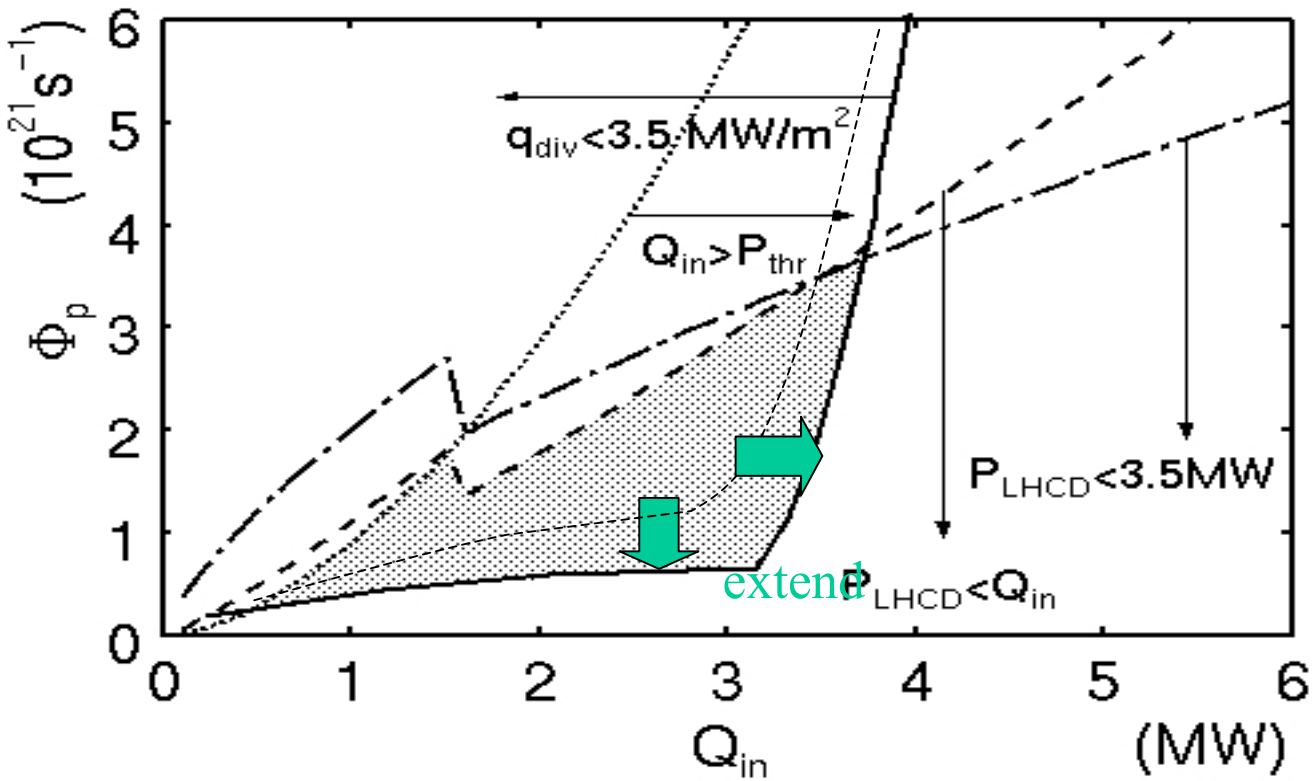
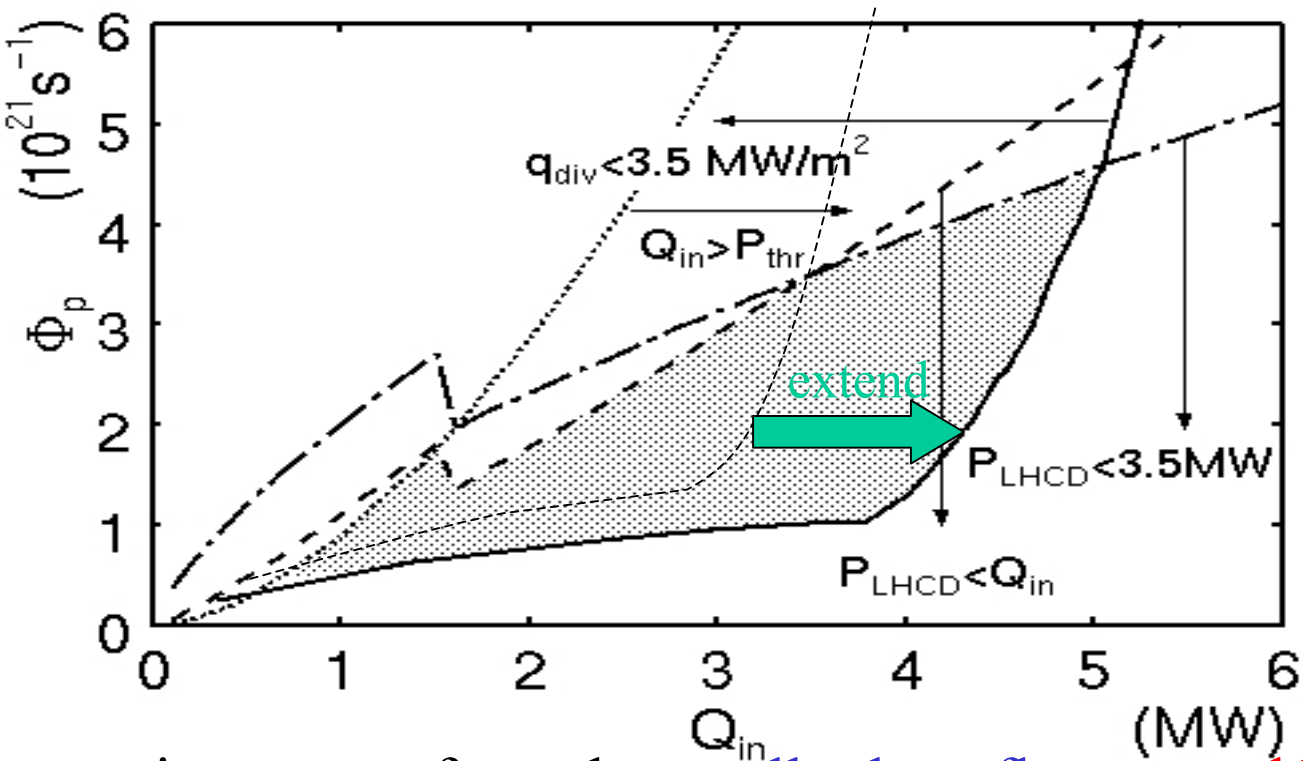
[10] S.Zhu, Contrib. Plasma Phys. 40(2000)322.
[11] T.Takizuka, et al., Development of Database for the Divertor Recycling in JT-60U and Its Analysis, JAERI-Research 2003-010

Gas puffing into the divertor region



This extension comes from the transition of low to high recycling state in the lower Φ_p region with gas puffing effect(N_{puff}~Φ_p).

Impurity seeding in the edge region



This extension comes from the smaller heat flux caused by impurity seeding(f_{imp}=0.3 --> 0.6).

For high Q_{in} region of operational space, upper boundary of Φ_p is the available LHCD power.

The LHCD power is a key parameter to extend the operation density of core plasma.