

Study of Power Exhaust in Edge and Divertor of the SlimCS Demo Reactor

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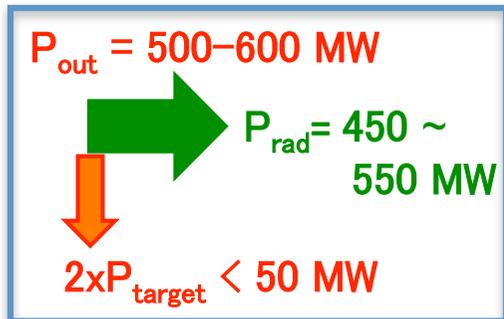
1. Introduction: power exhaust for DEMO divertor
2. Power handling in divertor (**SOLDOR/NEUT2D**)
geometry effect on detachment, Ar seeding
3. Development of **Monte-Carlo simulation for Ar impurity seeding (SONIC)**
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1. Introduction

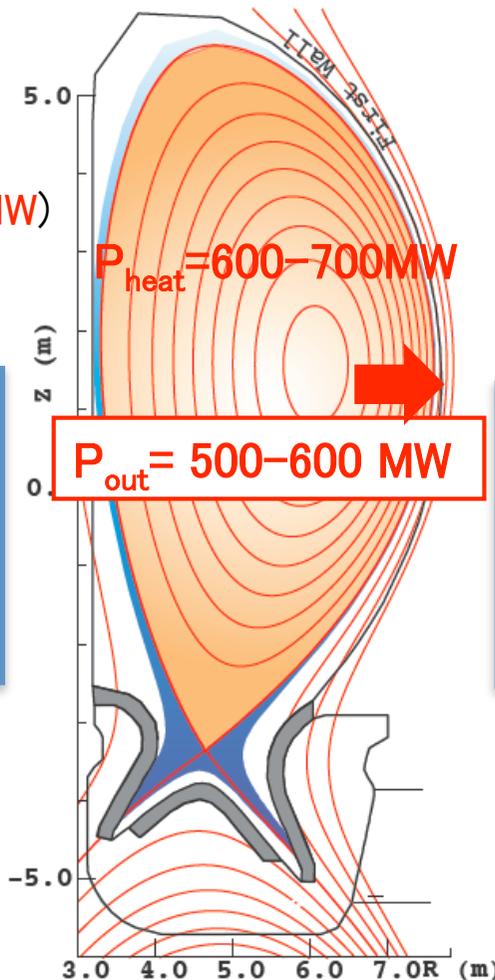
- "**SlimCS**" aims $P_{fus} \leq 3$ GW ($P_{heat} = 600 \sim 700$ MW) with $A=2.6$ and reduced-size CS.
 \Rightarrow Power exhausting to SOL is 5-6 times larger and R is smaller than ITER.
 Power handling by plasma operation, divertor design, and target engineering is the most important issue for the reactor design.

SlimCS

$P_{fusion} = 2.95$ GW
 ($P_{heat} = P_{\alpha} + P_{ax} = 600 \sim 700$ MW)

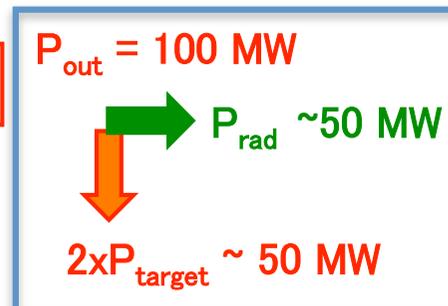


Major radius : $R_p = 5.5$ m
 Minor radius : $a_p = 2.1$ m
 Plasma current : $I_p = 16.7$ MA
 Toroidal field : $B_t = 6.0$ T
 Plasma volume : $V_p = 941$ m³

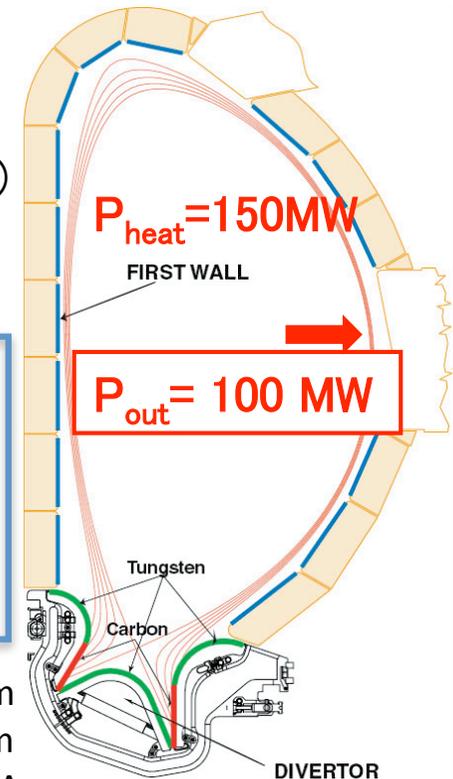


ITER

$P_{fusion} = 0.5$ GW
 ($P_{heat} = P_{\alpha} + P_{ax} = 150$ MW)



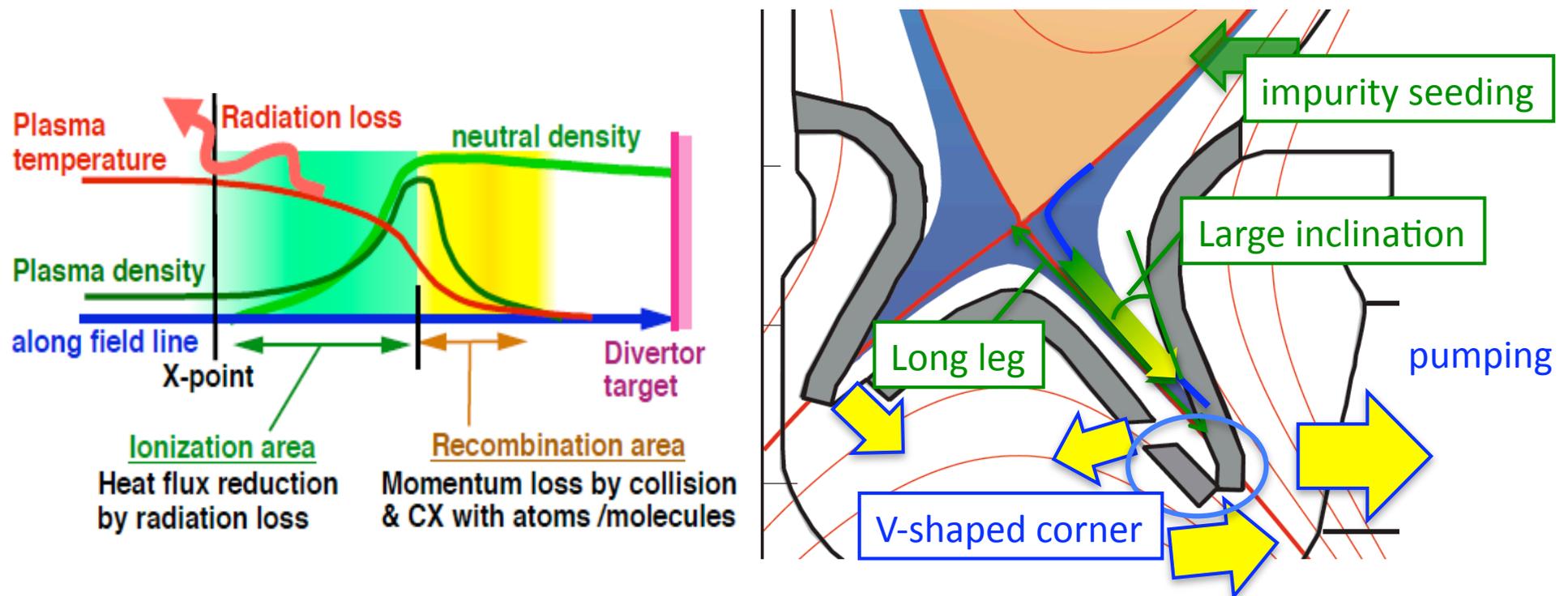
Major radius : $R_p = 6.2$ m
 Minor radius : $a_p = 2.0$ m
 Plasma current : $I_p = 15$ MA
 Toroidal field : $B_t = 5.3$ T
 Plasma volume : $V_p = 830$ m³



Divertor concept for ITER and DEMO reactors

Power handling in *SlimCS* divertor was studied using **SOLDOR/NEUT2D code** \Rightarrow **SONIC**
Design concept for the ITER divertor is applied/extended to the DEMO divertor:
“*divertor detachment*” ($T_e \sim$ a few eV) is a key for the power handling

- (1) Divertor leg and inclination of the target** are larger than ITER
 \Rightarrow increase radiation, CX & volume recombination at upstream, reducing q^{target} .
- (2) V-shaped corner** \Rightarrow enhance recycling near the strike-point.
- (3) impurity seeding** such as Ar (Ne, N₂, Kr, Xe) \Rightarrow enhance edge & divertor radiation.



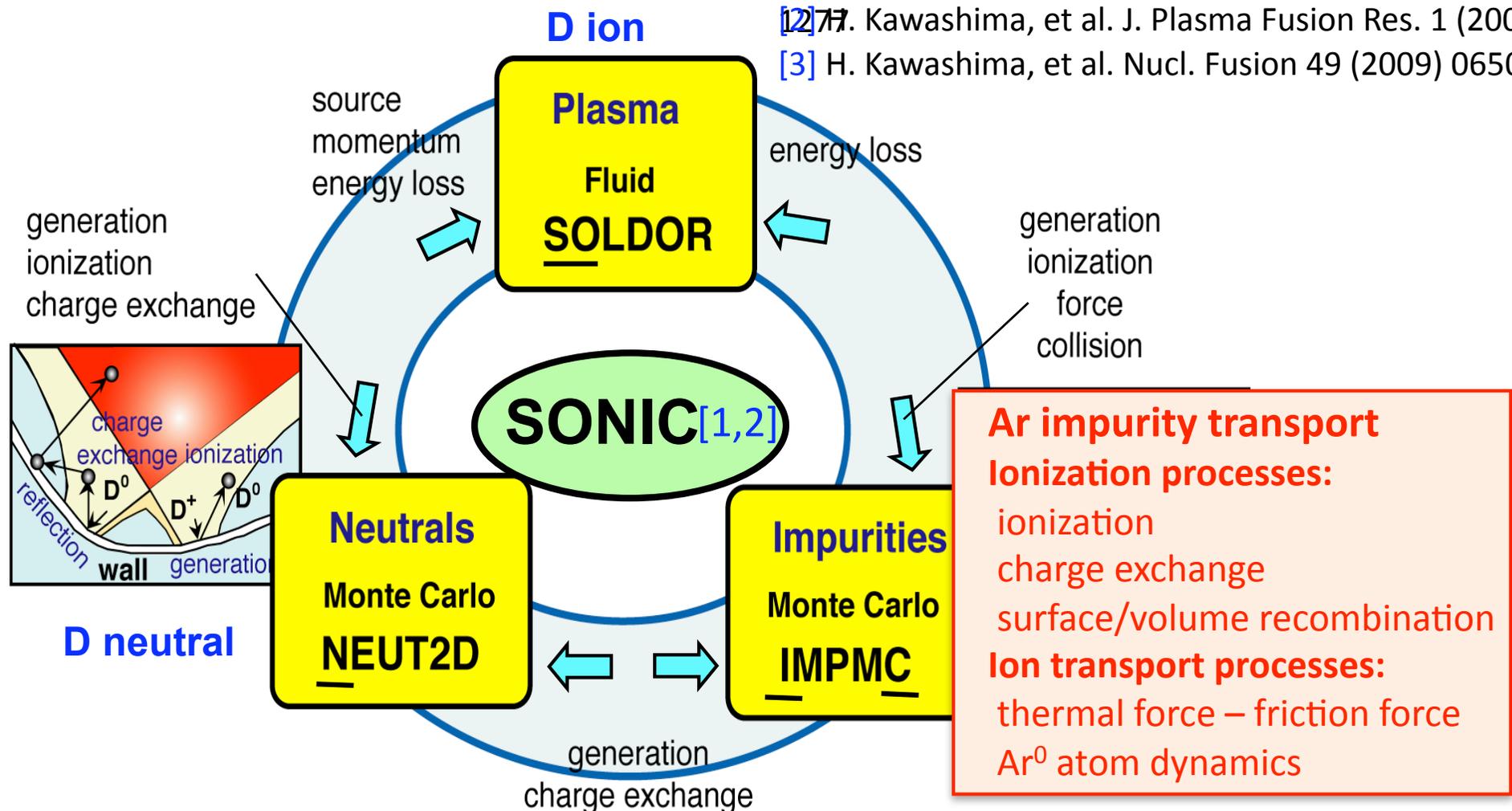
SONIC : self-consistent coupling with Ar impurity Monte Carlo has been developed for Ar seeding and transport

- **SOLDOR/NEUT2D** were used for DEMO divertor design, where Ar impurity radiation with *non-coronal model*: $P_{rad} = L(T_e, \tau_r) n_z n_e$, and constant n_{Ar}/n_i was applied. [3]

[1] K. Shimizu, et al., J. Nucl. Mater. 313-316 (2003)

[2] H. Kawashima, et al. J. Plasma Fusion Res. 1 (2006) 31

[3] H. Kawashima, et al. Nucl. Fusion 49 (2009) 065007



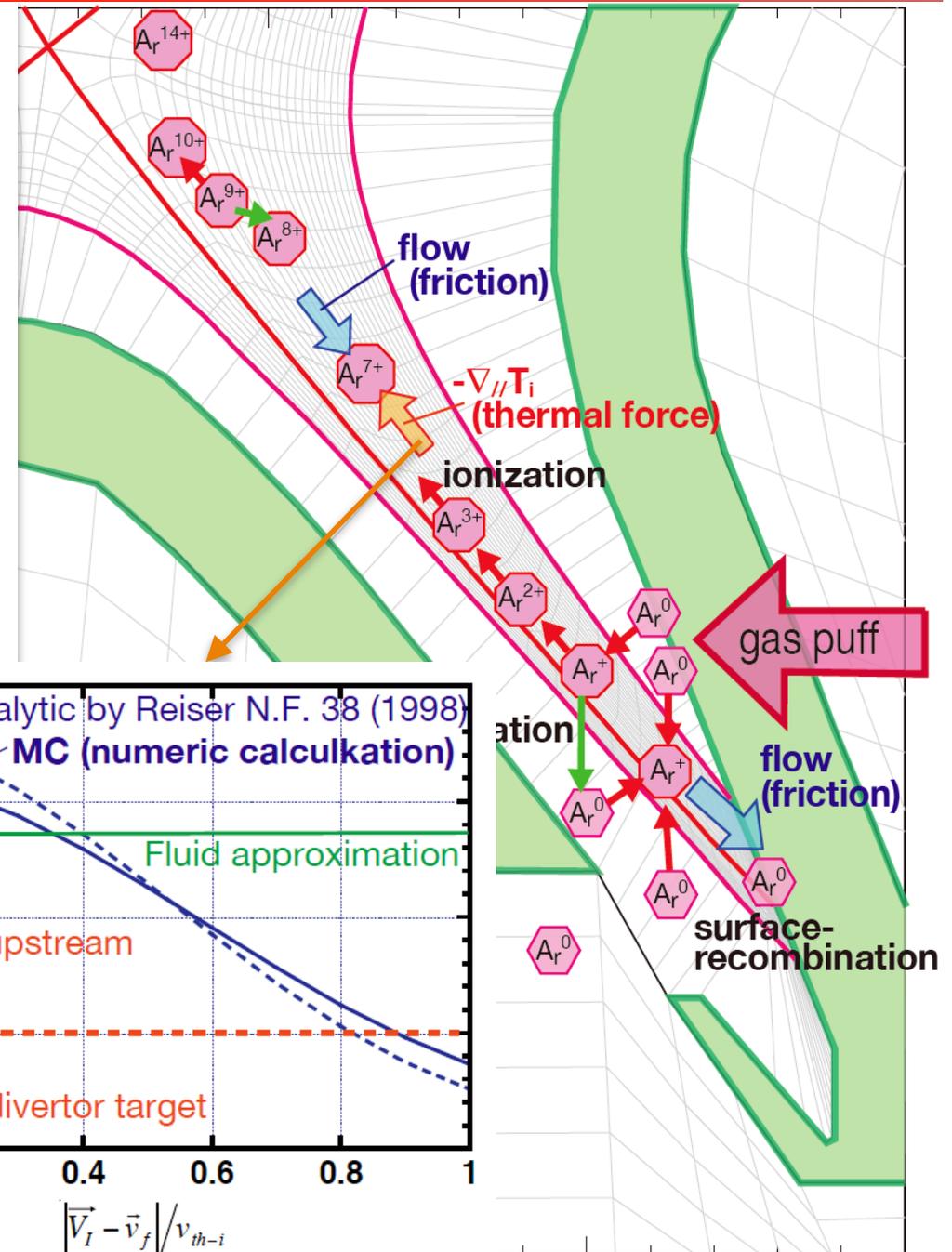
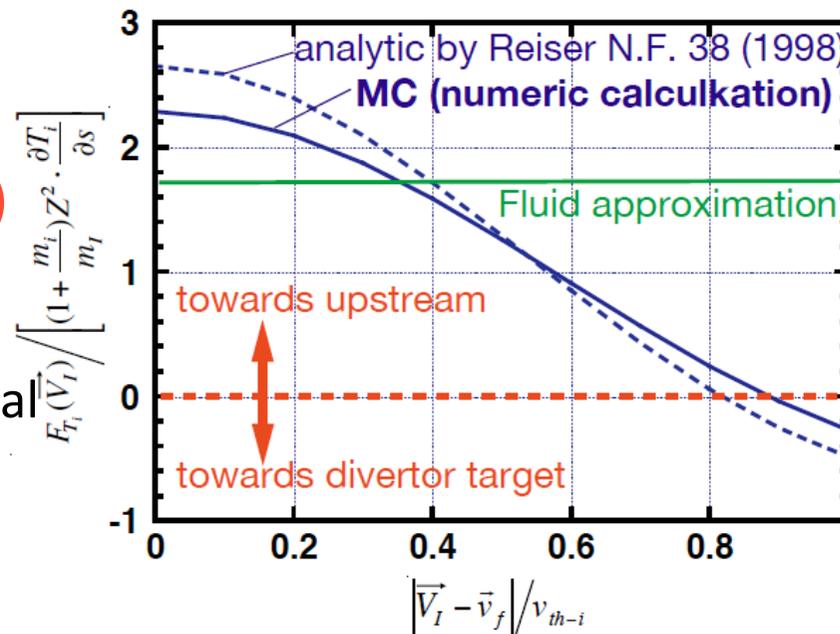
MC approach has advantages to impurity modelling

Most impurity transport processes are incorporated in original formula:

- Tracking impurity neutrals and ions
 \Rightarrow CX-loss, n-collision, recycling etc.
 Radiation & Recombination at multi-charge states
- Kinetic effect \Rightarrow Thermal force
- Gyro-motion \Rightarrow Erosion (for PWI)

For self-consistent coupling of MC code, problems (long calculation time and MC noise) have been solved.

Kinetic thermal force (F_{Ti}) decreases with impurity ion speed (v_I) approaching to ion thermal velocity (v_{th-i}).



2. Simulation of power handling in the SlimCS divertor

SOLDOR/NEUT2D was used for the DEMO divertor design with Ar impurity radiation.

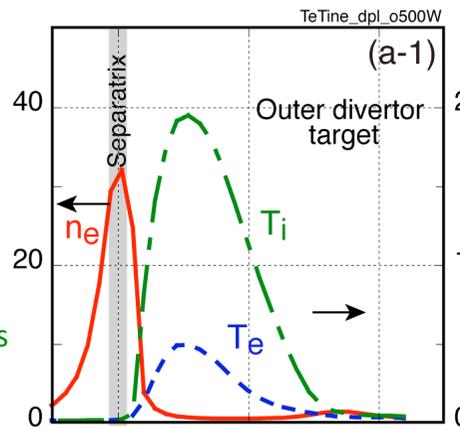
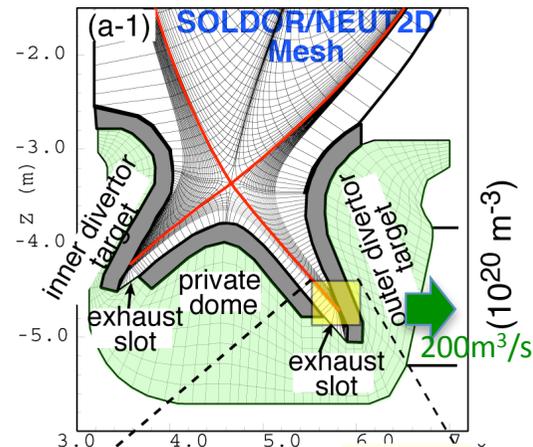
H. Kawashima, et al. Nucl. Fusion 49 (2009) 065007

Input parameters at edge-SOL

$$P_{\text{out}} = 500 \text{ MW}, \Gamma_{\text{out}} = 0.5 \times 10^{23} \text{ s}^{-1} \text{ (r/a=0.95)}$$

$$\chi_i = \chi_e = 1 \text{ m}^2\text{s}^{-1}, D = 0.3 \text{ m}^2\text{s}^{-1}$$

Case-1: pumping from bottom corner with gas puff and impurity seeding:



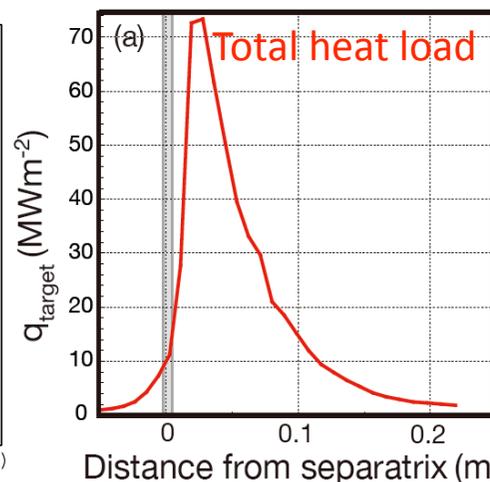
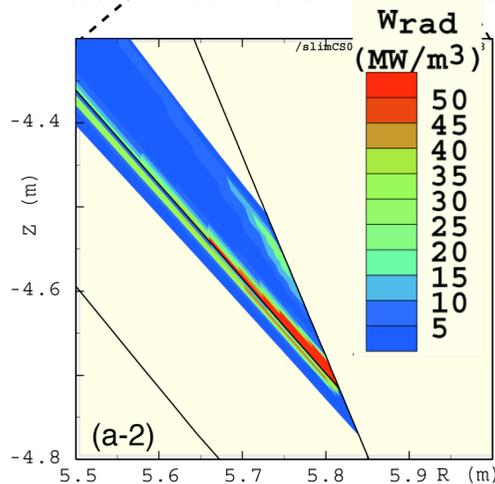
D_2/T_2 gas puff: $\Gamma_{\text{puff}} = 1 \times 10^{23} \text{ s}^{-1}$ ($200 \text{ Pam}^3\text{s}^{-1}$)
 Ar fraction: $(n_{\text{Ar}}/n_i)_{\text{o-div}} = 2\%$, $(n_{\text{Ar}}/n_i)_{\text{edge-SOL}} = 1\%$
 applying *non-coronal model*: $P_{\text{rad}} = L(T_e, \tau_r) n_z n_e$

Divertor pumping speed at exhaust duct:
 $S_{\text{pump}} = 200 \text{ m}^3\text{s}^{-1}$ is given.

- At the inner target, divertor is detached and $q^{\text{target}} < 5 \text{ MW/m}^2$.

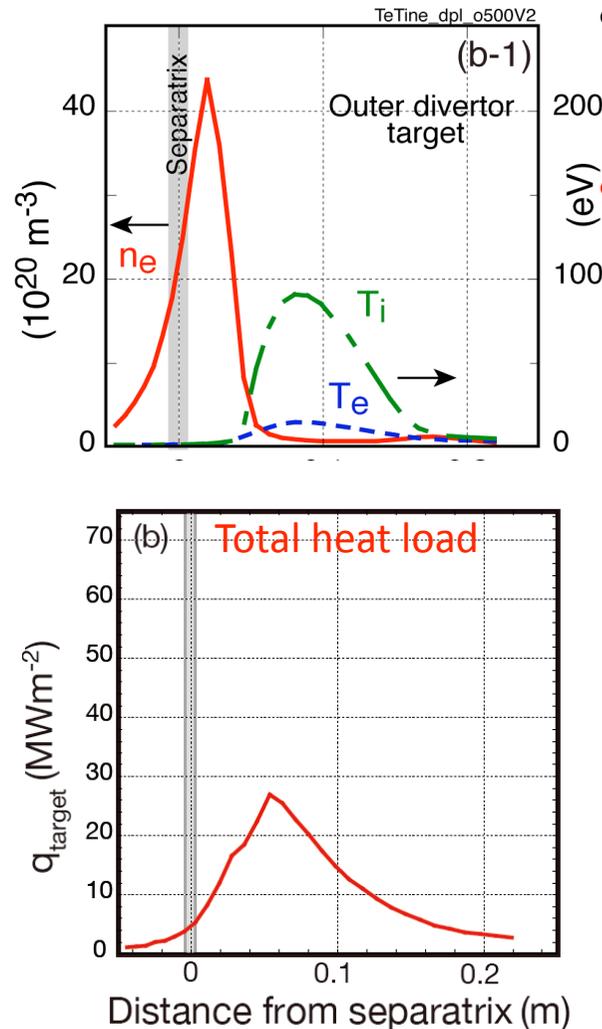
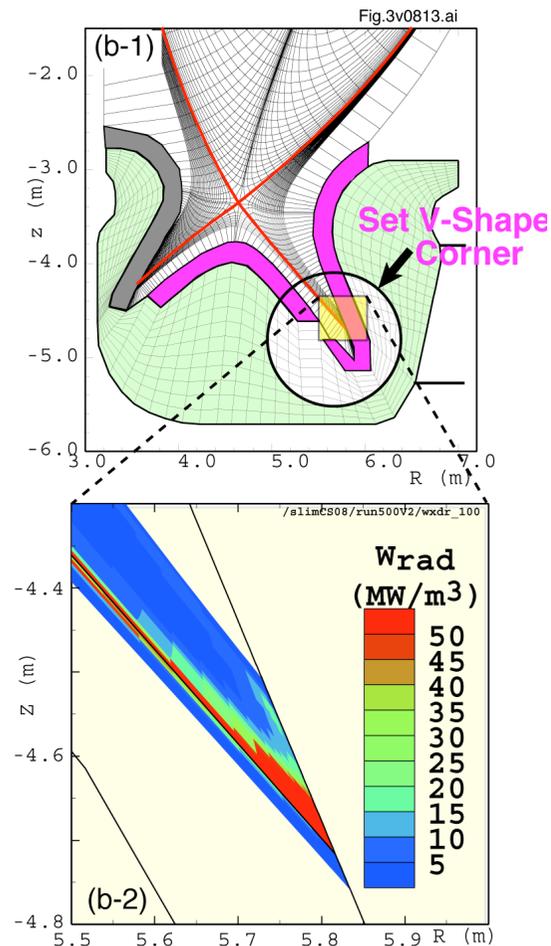
- At the outer target, high temperature at the strike-point:

peak $T_e \sim 50 \text{ eV}$ and $T_i \sim 200 \text{ eV}$, giving severe peak heat load $\sim 70 \text{ MW/m}^2$!



2.1 Power handling in divertor: **divertor geometry**

Case-2: Concept for the ITER divertor, “V-shaped corner”, is investigated



- Divertor recycling is increased from 3.7×10^{24} to $4.2 \times 10^{24} \text{ s}^{-1}$.

- Radiation loss at the outer divertor is increased at upstream of the strike point **from 85 to 142 MW**:
Total $P_{\text{rad}}(\text{edge}+\text{div.}) = 390 \text{ MW}$
($P_{\text{rad}}^{\text{edge}} \sim 130 \text{ MW}$, $P_{\text{rad}}^{\text{div}} \sim 260 \text{ MW}$)

- Peak $T_e \sim 20 \text{ eV}$, $T_i \sim 90 \text{ eV}$ are smaller by the factor of $1/2 \sim 1/2.5$.

Conduction/convection heat load is reduced in the low T_e divertor:

Peak heat load is reduced from 70 MW/m^2 to 27 MW/m^2 .

Recombination and radiation power loads become important in high recycling divertor, while Conduction/Convection heat load is reduced

- Evaluation of major heat load on the target

$$q_{\text{target}} = \underbrace{\gamma \cdot n_d \cdot C_{sd} \cdot T_d}_{\text{Transport component (incl. electron\&ion-conduction/convection)}} + \underbrace{n_d \cdot C_{sd} \cdot E_{\text{ion}}}_{\text{Surface-recombination loss}} + \underbrace{f(P_{\text{rad}})}_{\text{radiation power load}} + \underbrace{f(1/2 m v_0^2 n_0 v_0)}_{\text{neutral power load}}$$

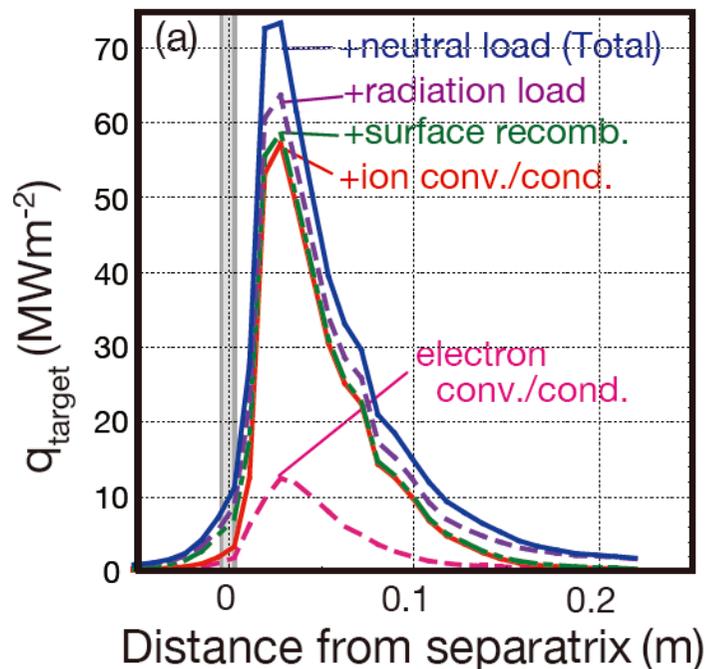
Transport component
(incl. electron&ion-
conduction/convection)

Surface-recombination
loss

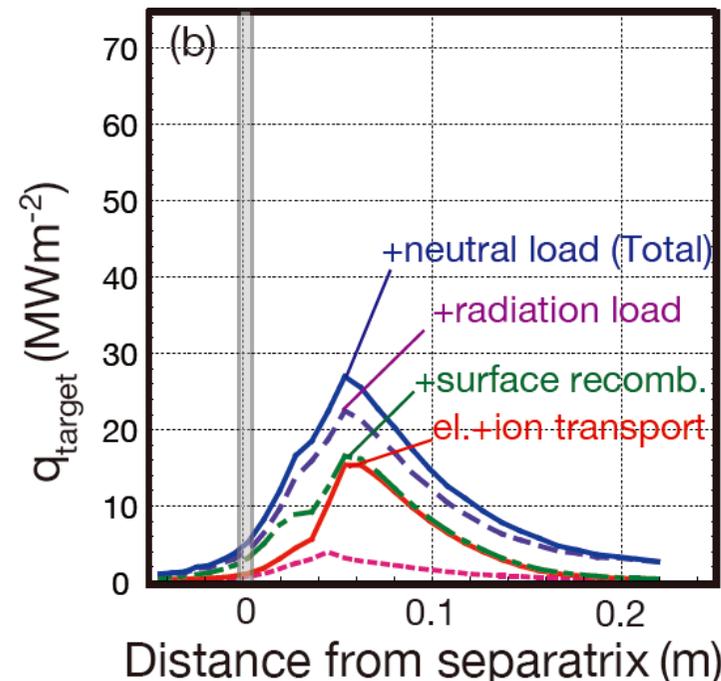
radiation
power load

neutral
power load

Case-1: pumping from bottom corner



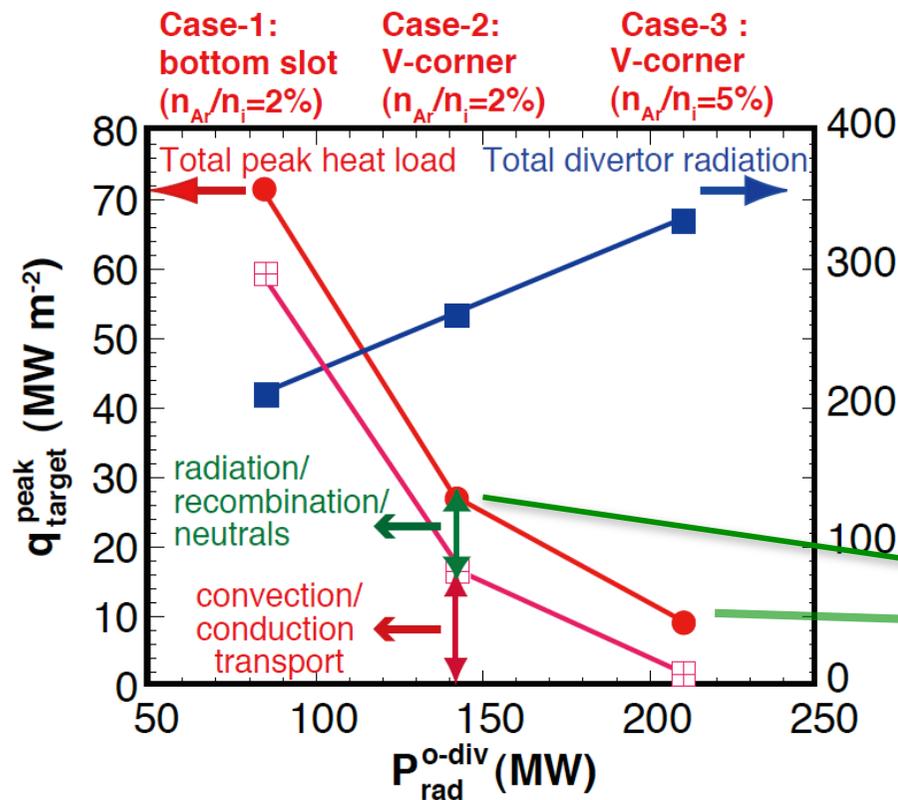
Case-2: "V-shaped divertor"



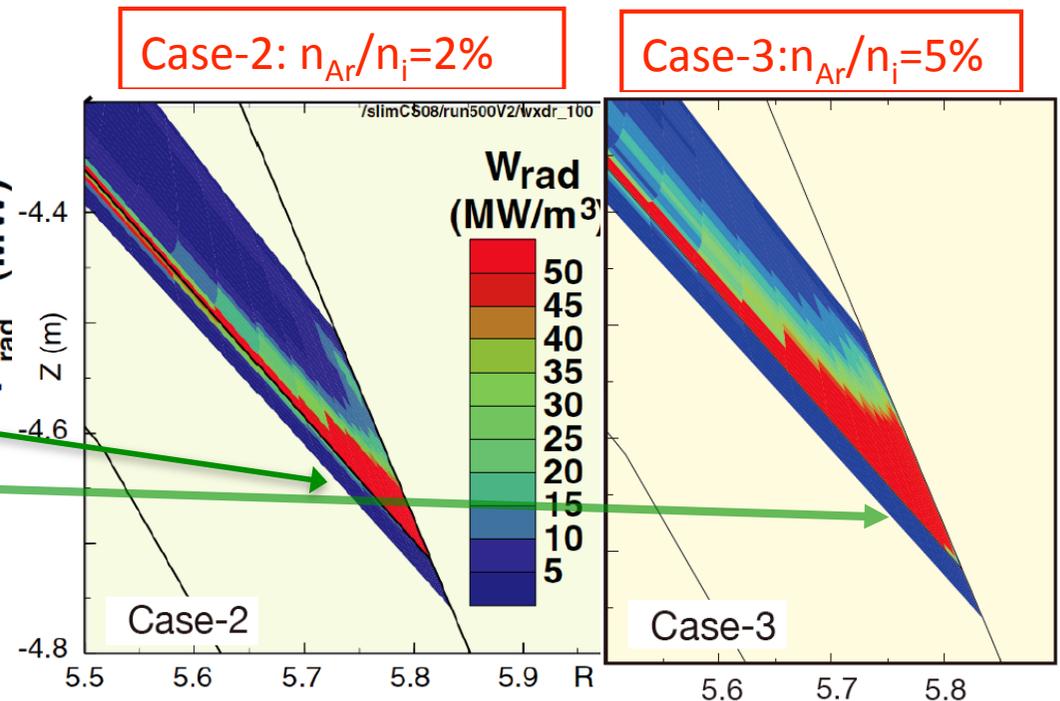
2.2 Power handling in divertor: increasing Ar seeding

Case-3: increasing Ar ion in the outer divertor $(n_{Ar}/n_i)_{odiv}=5\%$ is investigated.

- Large heat load extends in a wide divertor area, when P_{rad}^{tot}/P_{out} increased to $\sim 92\%$:
Peak heat load in the detached divertor, $q^{peak} \sim 9 \text{ MWm}^{-2}$, is attributed to **Radiation/Neutral flux** and **their distributions in the divertor**.
- *Modelling (understanding) of impurity transport in the edge and divertor is crucial for improvement of the heat handling scenario with single/multi-impurity seeding.*



Intense radiation area (and plasma detachment) extending to wide and upstream in the divertor



3. Development of MC modelling for Ar seeding

MC modelling for Ar seeding was investigated in the high recycling divertor:

- Self-consistent coupling of the fluid plasma, MC neutral and impurity has been developed for the reactor divertor.

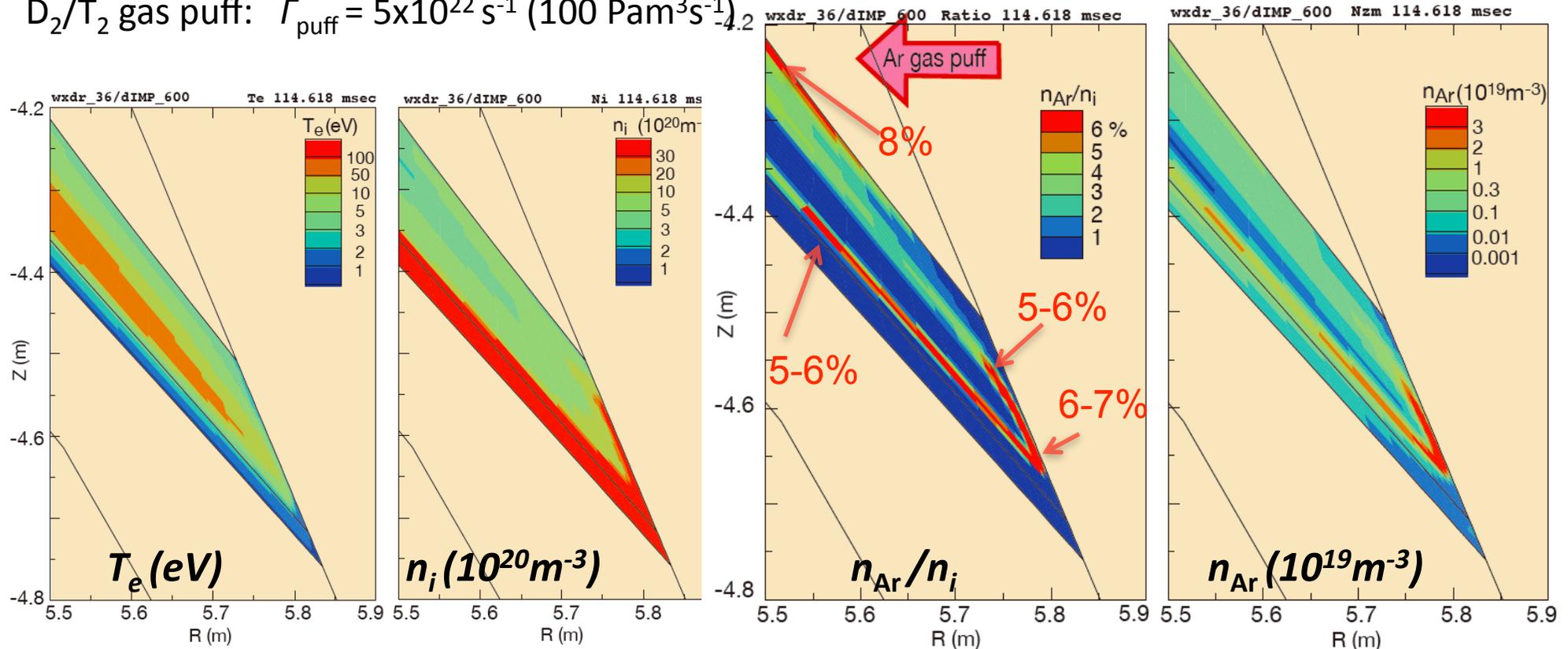
Ar transport was simulated till $t \sim 10$ ms (typical time scale of transport in divertor):

Ar recycling is enhanced near the target (friction force is dominant)

➔ Influence of thermal force on impurity transport is observed near the separatrix

Ar seeding rate : $\Gamma_{Ar} = 2 \times 10^{21}$ Ar/s ($4 \text{ Pam}^3\text{s}^{-1}$)

D_2/T_2 gas puff: $\Gamma_{puff} = 5 \times 10^{22} \text{ s}^{-1}$ ($100 \text{ Pam}^3\text{s}^{-1}$)



Detachment was different depends on initial condition of the divertor

Self-consistent solution for $P_{out} = 500 \text{ MW}$, $\Gamma_{Ar} = 2 \times 10^{21} \text{ Ar/s}$ was obtained using the different Initial Conditions:

IC-1: background plasma in Case-2 ($n_{Ar}/n_i = 2\%$) was used (partially detached).

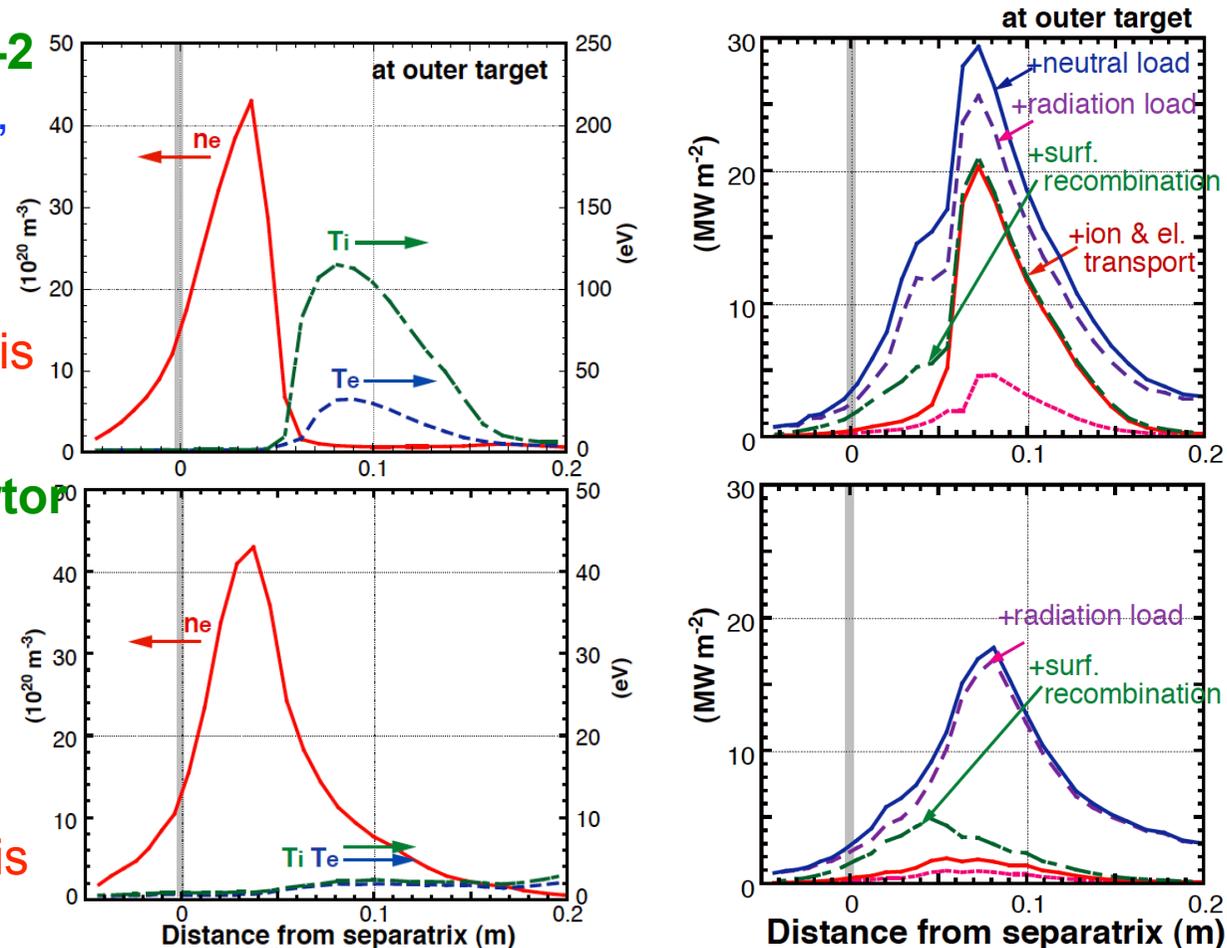
IC-2: background plasma of full detached divertor was used.

- Different divertor plasma profiles are sustained *after time scale of transport in divertor, but still transient at the upstream SOL/edge.*

IC-1: plasma from Case-2

Detached near separatrix, and attached at the outer flux surfaces

→ max. $q_{div} \sim 28 \text{ MWm}^{-2}$
where transport heat flux is dominant.



IC-2: full detached divertor

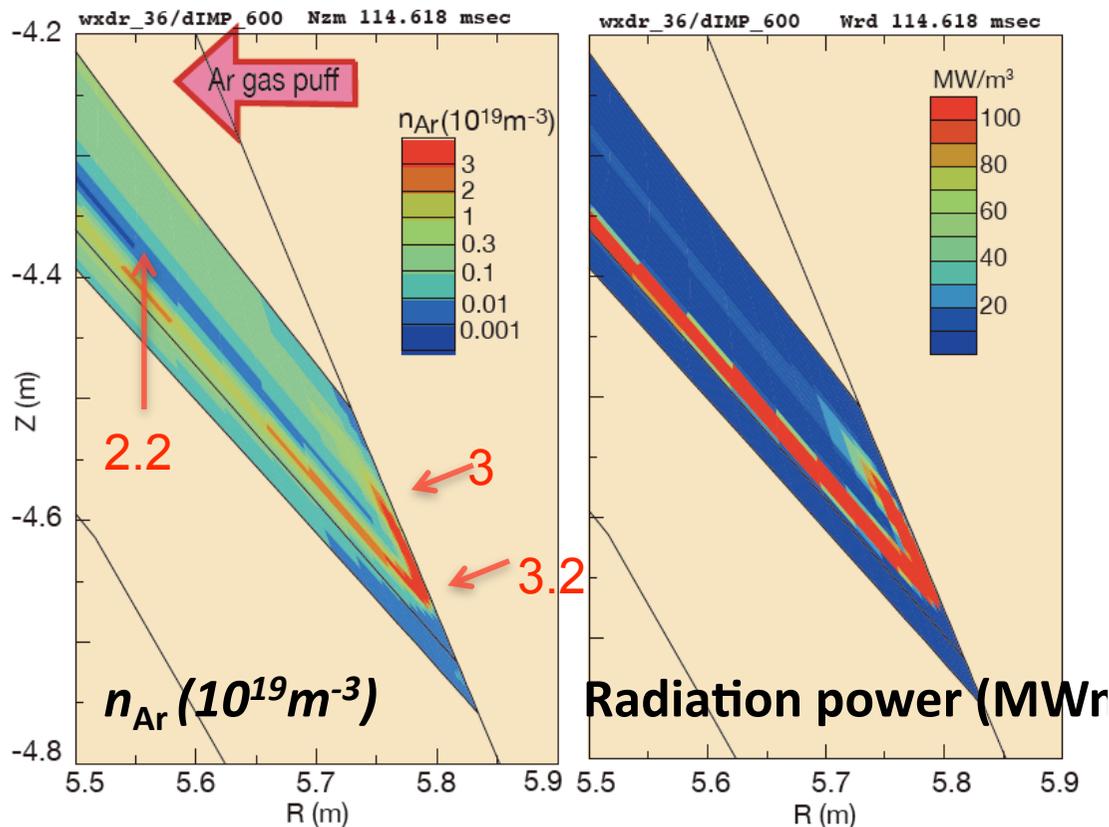
Full detached divertor is sustained, while radiation loss near the target becomes significant

→ max. $q_{div} \sim 18 \text{ MWm}^{-2}$
where radiation heat flux is dominant.

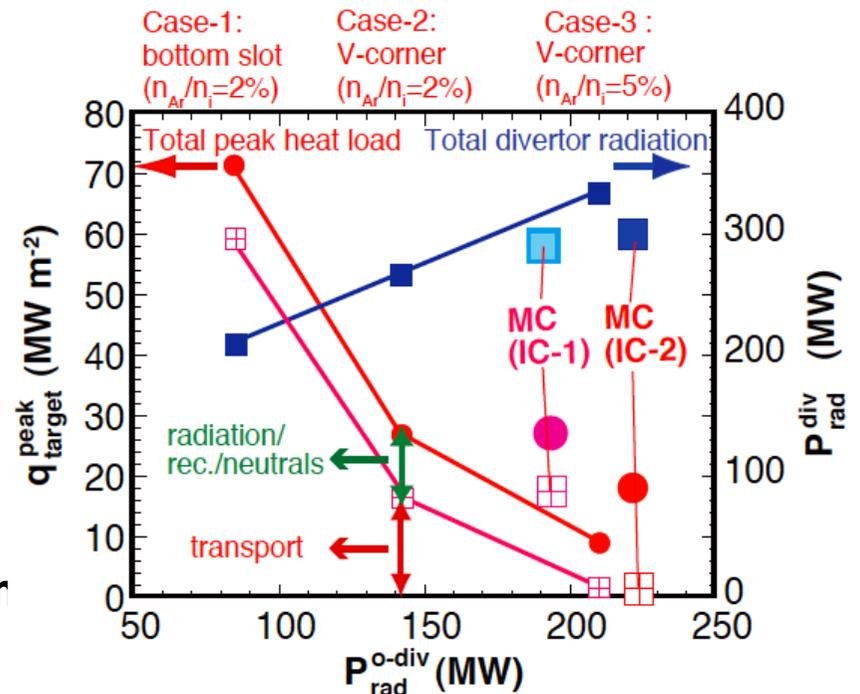
Radiation power load from MC modelling (div. transport time scale) is dominant more than *Non-coronal model and Constant n_{Ar}/n_i*

- Region with large radiation loss ($>50 \text{ MWm}^{-3}$) is localized just above the target, while the full detachment is sustained in divertor transport time scale (IC-2 case).
 - Ar transport to the upstream SOL/edge is not long enough: radiation at SOL/edge, $P_{rad}^{edge} \sim 20 \text{ MW}$, is smaller than $P_{rad}^{edge} \sim 130 \text{ MW}$ ($n_{Ar}/n_i \sim 1\%$)
- ➔ Investigation of Ar transport and radiation power at SOL/edge is necessary to determine appropriate or combination of the radiators.

IC-2: full detached divertor case



Radiation power and its heat load contribution



4. Summary of power exhaust study for the DEMO divertor

- **Huge power handling ($P_{out} = 500\text{MW}$) for SlimCS ($P_{fusion} \leq 3\text{GW}$) was investigated**

The previous work by SOLDOR&NEUT2D (*non-coronal model & constant n_{Ar}/n_i*) showed

Intense Ar concentration ($n_{Ar}/n_i \sim 5\%$) in the long-leg and V-shaped divertor produced the detached divertor ($P_{rad}^{tot}/P_{out} \sim 92\%$: $P_{rad}^{SOL/edge}/P_{out} \sim 26\%$ and $P_{rad}^{div}/P_{out} \sim 66\%$)

⇒ **Peak heat load $q_{target} \sim 9\text{MW/m}^2$, which was attributed mostly to *radiation and neutral flux are dominant***, compared to transport (conv. and cond.) heat flux.

Distribution of the radiation region over a wide area (edge and divertor) will be required in order to avoid local overheating of Plasma Facing Components.

- **SONIC with impurity MC has been developed for the Ar impurity seeding.**

Self-consistent coupling of the fluid plasma, MC neutral and impurity has been developed for the reactor divertor:

Ar transport was simulated until $t \sim 10$ ms (time scale of impurity transport in divertor), *but still transient at the upstream SOL/edge.*

⇒ **Region with large radiation loss ($>50 \text{ MWm}^{-3}$) is localized just above the target, while the full detachment is sustained in divertor transport time scale.**

Radiation profile in steady-state and penetration to SOL/ edge/ core plasma will be calculated to determine an appropriate radiator or the combination.

Issues for the DEMO divertor design

- *Understanding of physics process and Improve of modelling* under the ITER/DEMO-level high recycling divertor are required, such as atomic/molecule/impurity processes (n-n/i-n collision, photon absorption, MAR) , thermal stability of the divertor plasma with seeding and metallic (high-Z) impurities.
- Design for particle control should be improved to satisfy DEMO divertor functions:
He exhaust requires the large divertor pumping
↔ Formation of the detached divertor requires high neutral pressure and radiation.
Development of SONIC with multi-species (Ar and He) MDs started from 2009.

Future issues in power handling scenario:

- Large power handling at the main SOL and Edge is required for the DEMO plasma:
Restrictions of the power handling (n_{imp}/n_i and $P_{rad}^{SOL/edge}$) such as due to influence of the divertor and degradation of core plasma performance is investigated.
- Desirable heat load of tentative target design (W, RAFMS, water-cooling) is 5-7MWm⁻².
⇒ ***Development/ improvement of plasma operation, divertor design, and target engineering are required for consistent heat handling scenario.***

Issues for the DEMO divertor (in addition)

Future issues in power handling scenario for engineering and PSI:

For the *divertor target* of W (PFC) & RAFM (structure material) & water cooling, allowable heat flux is tentatively expected to 5-7 MW/m².

➔ Design of materials, their specific joining and heat sink will be improved to increase q_{\max} and their engineering reliability.

Plasma Facing Component issues for W-PWI are pointed out in order to extrapolate from ITER to DEMO:

- Dependence/threshold of He irradiation effects, Neutron irradiation effects (defect, blistering by ions, increasing DBTT&T-retention) on temperature, fluence and energy under ITER-level conditions.
- Target design/arrange of mono-block armors and melt-layer dynamics.

On the other hand, **fluences of D/T/He ions and neutrons in the DEMO reactors-level** are far beyond existing database.

Estimation of computer time for steady-state distribution($t \sim 1s$)

JAEA parallel computer: effective speed 20GFlops

IFARC parallel computer: effective speed 100TFlops

$$100TFlops/20GFlops = 5000 \text{ times faster}$$

SONIC calculation: 3ms \sim 9 hours

$$1s/0.003s = 333 \text{ times more required}$$

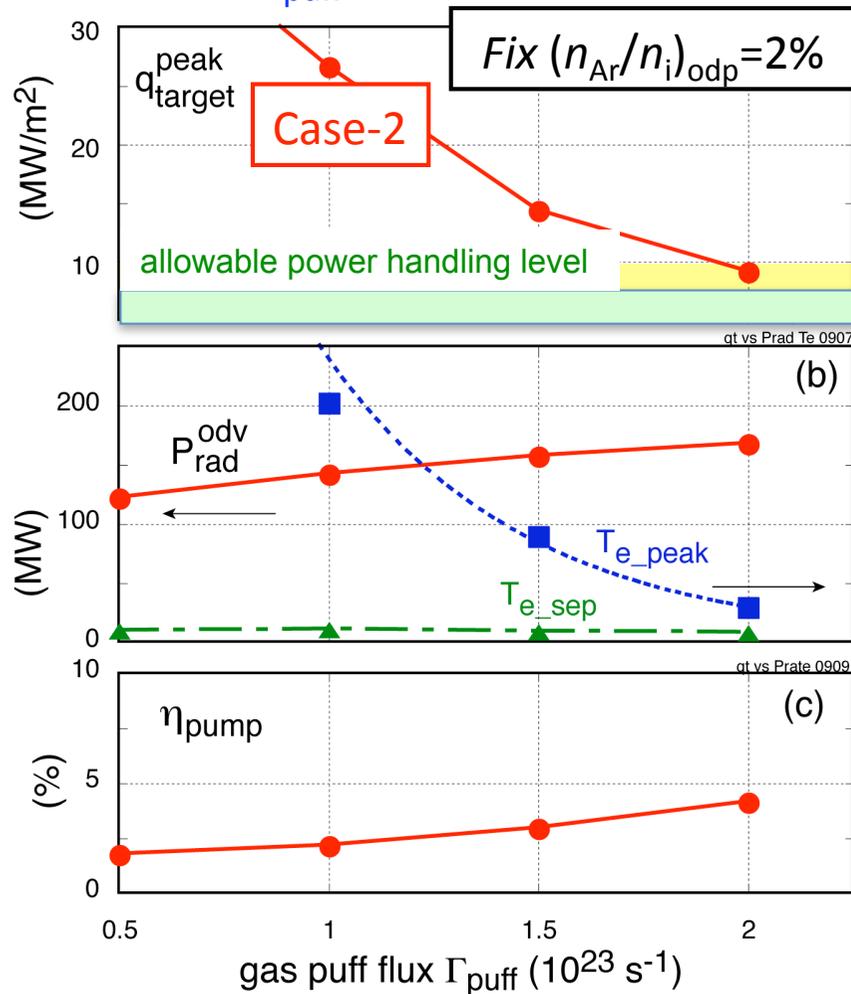
Then, SONIC calculation in steady-state (1s) will need

$$9 \text{ hrs} \times 333/5000 = 0.6 \text{ hr}$$

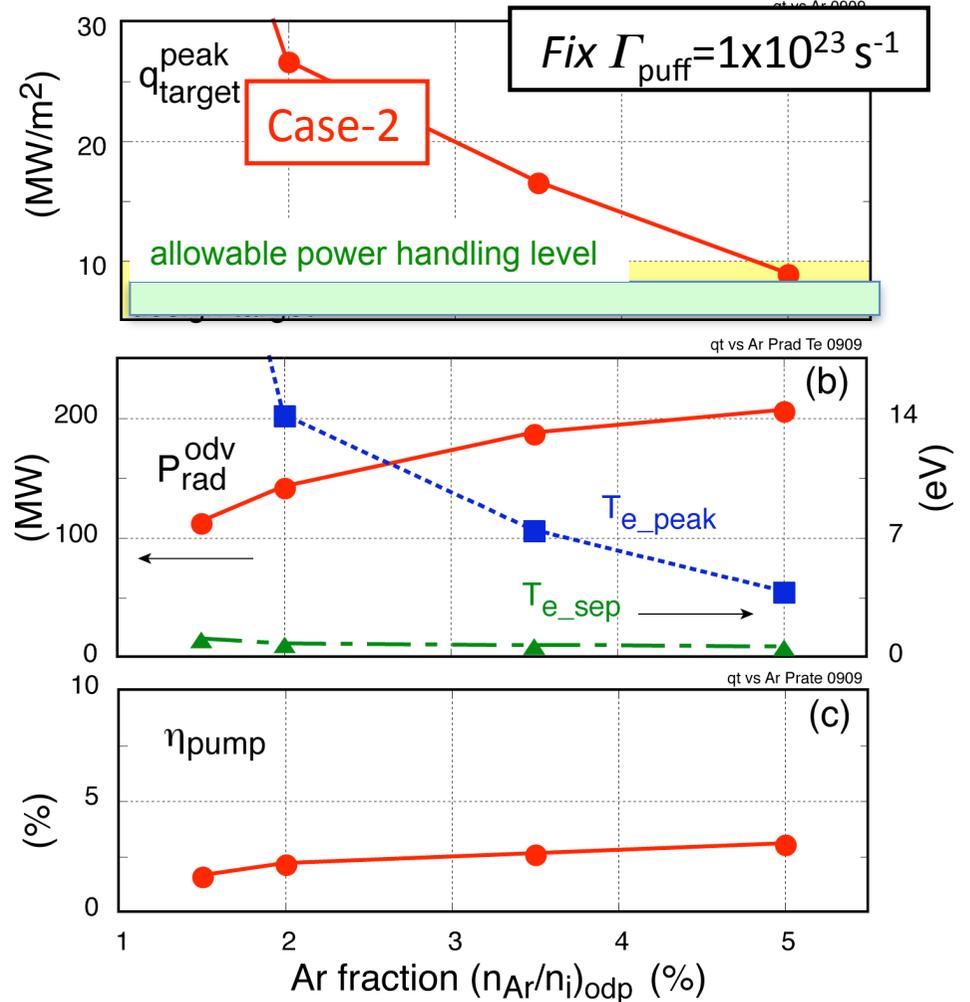
2.2 Gas puff and Impurity (Ar) seeding in V-shaped divertor

Additional gas puff/ Ar seeding will enhance divertor radiation for $q_{\text{target}} \sim 9 \text{ MWm}^{-2}$

- Gas puff (Γ_{puff}) is increased to $2 \times 10^{23} \text{ s}^{-1}$

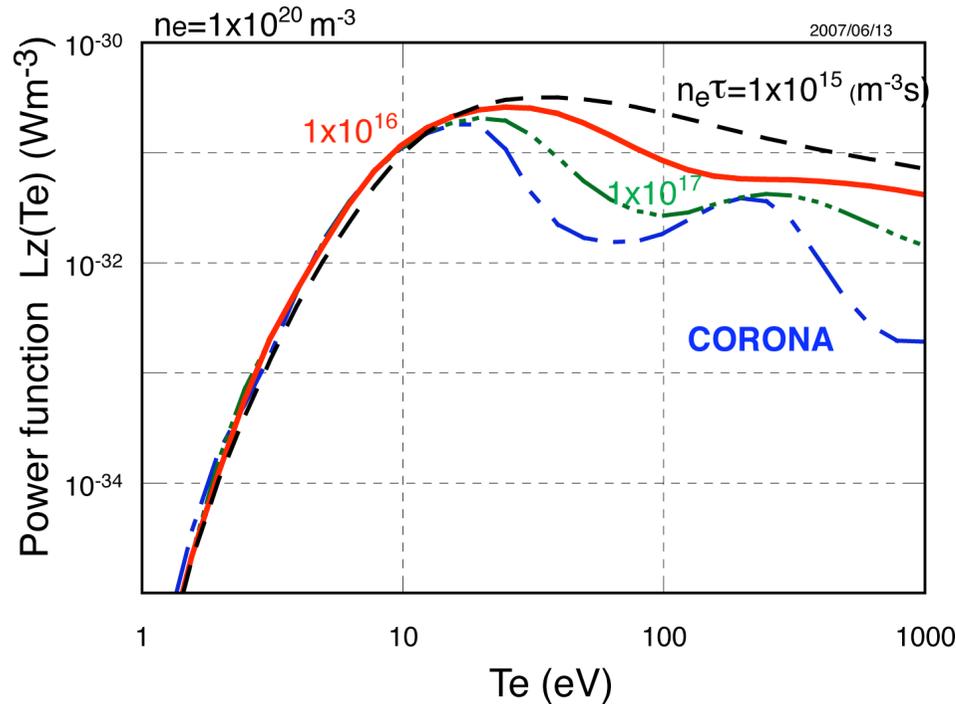


- Ar fraction is increased to $(n_{\text{Ar}}/n_{\text{i}})_{\text{odp}} = 5\%$



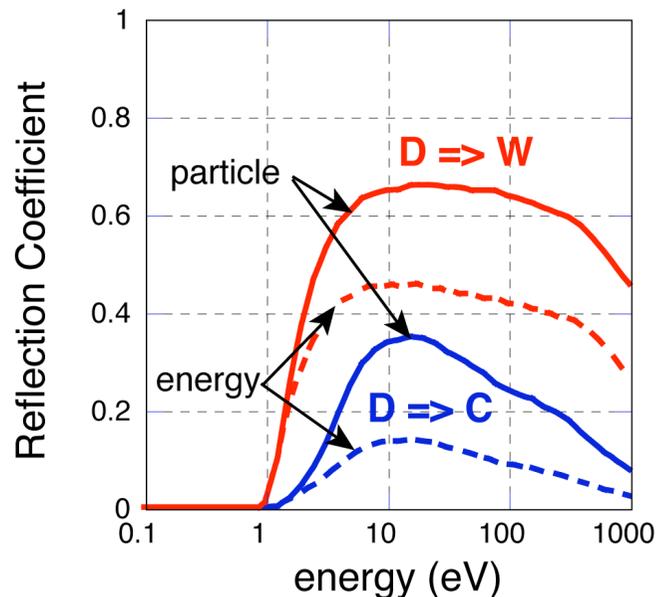
- Pumping rate η_{pump} is increased from 2% to 3-4% by increase the neutral density.

Impurity and neutral treatment



Impurity radiation: non-coronal model

- Ar fraction (n_{Ar}/n_i) is given.
- Radiation loss power is evaluated by $W_r = -n_e n_z L_z(T_e)$.
- Loss rate $L_z(T_e)$ is used on $n_e \tau_{\text{res}} = 1 \times 10^{16} \text{ s/m}^3$.

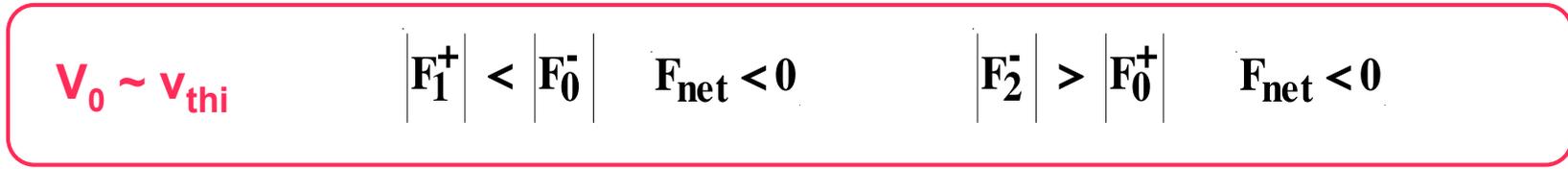
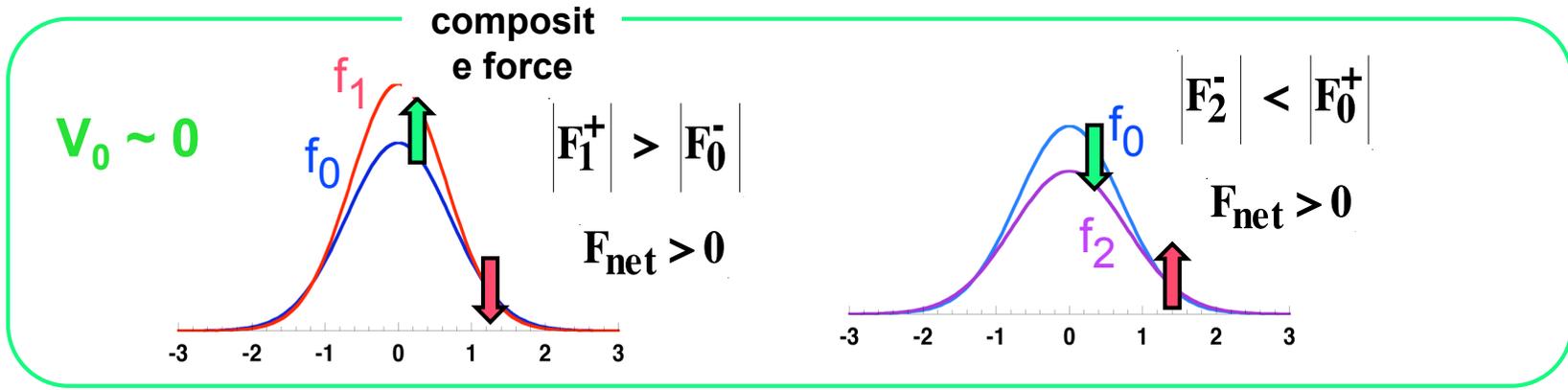
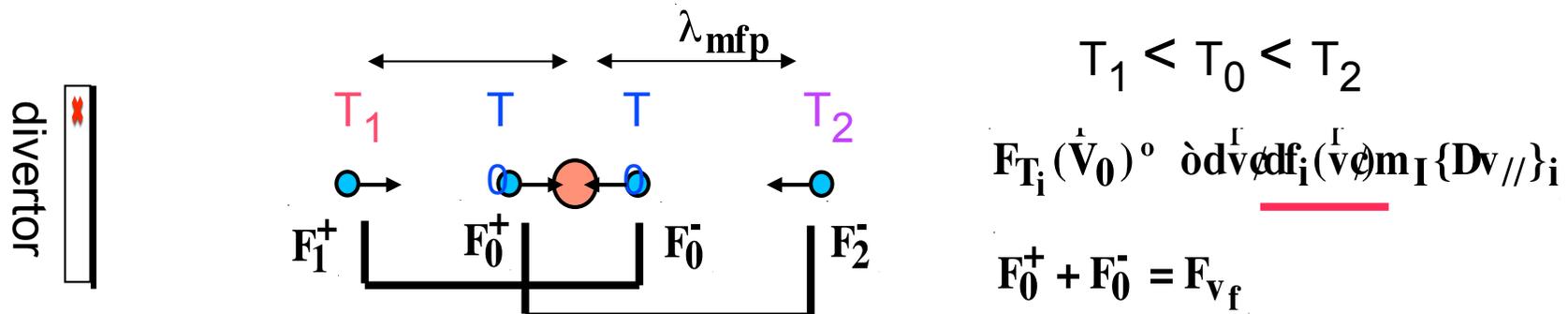


Neutral reflection: W target model

- Assumed W wall, which reflection coefficients of particle and energy are almost twice larger than that for carbon.

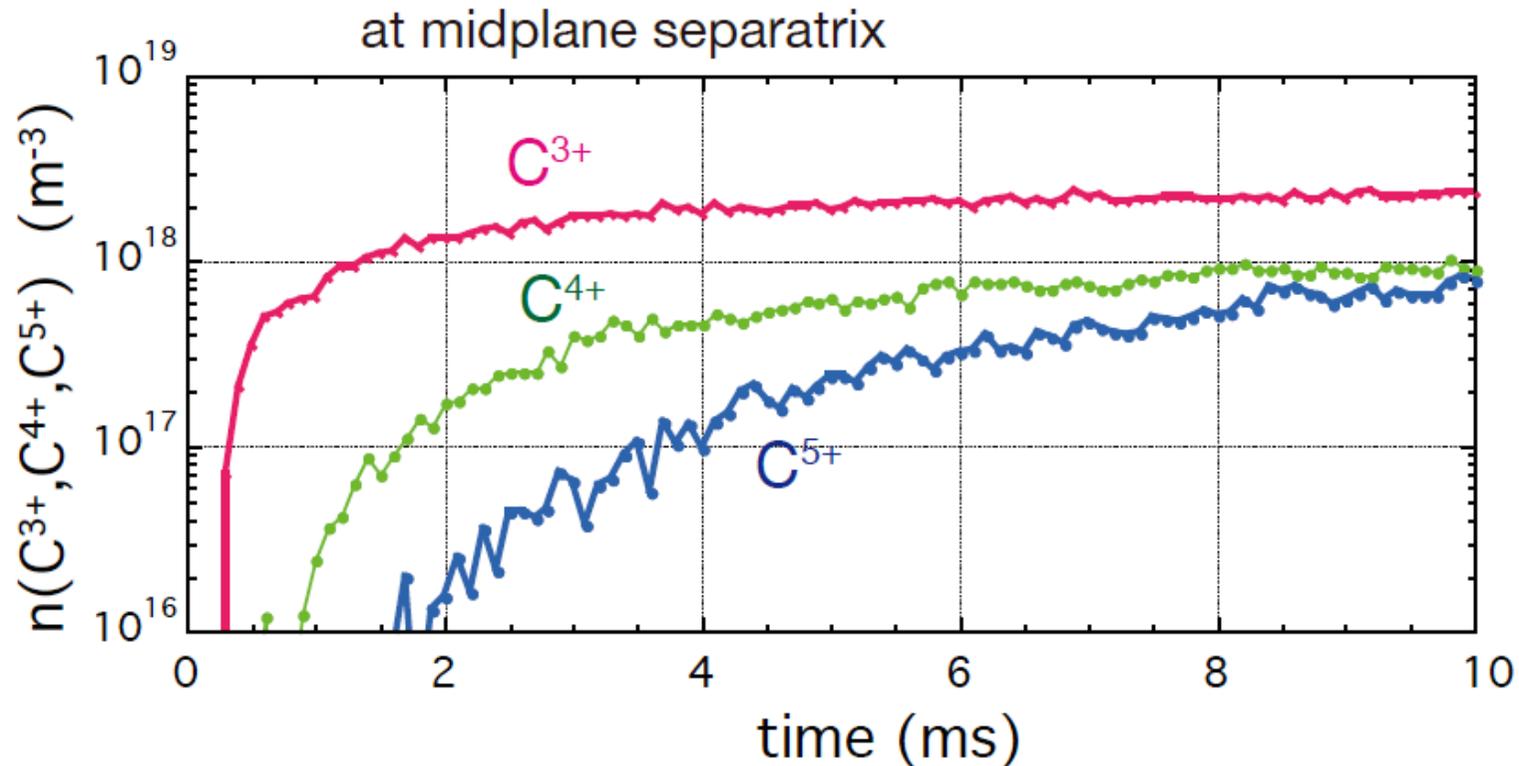
Understanding of Kinetic Thermal Force

The definition of kinetic thermal force : the momentum change by Coulomb collision is integrated over ion distribution distorted due to ion temperature gradient.



Impurity MC was calculated in the background plasma/
neutral distributions in the previous $(n_{Ar}/n_i)_{odiv} = 2\%$ case
Ar ions was traced up to $t = 3.8$ ms (transient phase)

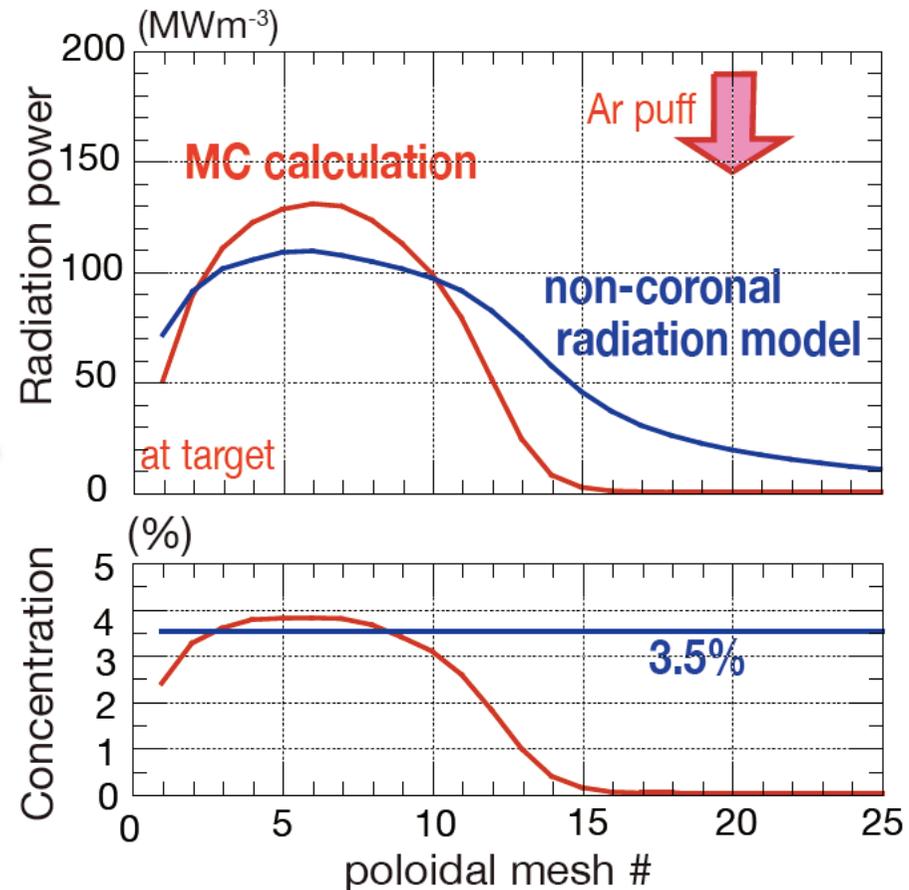
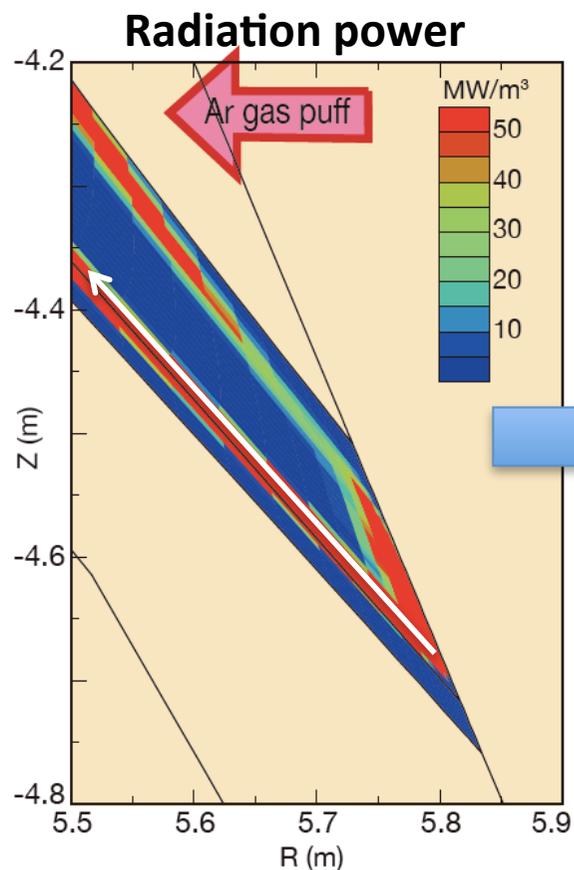
- Conversion of Carbon MC calculation was determined by impurities with higher charged-state.



Radiation profile (MC result) was localized above the target

- Radiation loss in the outer divertor was increasing during the MC calculation:
 $P_{\text{rad}}^{\text{o-div}} = 126 \text{ MW}$ at $t = 10 \text{ ms}$ was smaller than 140 MW for Case-2.
- Radiation profile (MC result) was rather localized above the target, compared to the non-coronal model with $(n_{\text{Ar}}/n_{\text{i}})_{\text{odiv}} = \text{const.}$

Calculation to the conversion (near steady-state) will show larger radiation power from higher charge-state Ar ions at the upstream of the target.



4. Issue for impurity: dilution & He exhaust

Ar seeding ($n_{\text{Ar}}/n_e=0.22 \Rightarrow 0.44\%$) reduces *Power to SOL* ($P_{\text{to-SOL}} = 600 \Rightarrow 480\text{MW}$), with expense of *lowering Fusion power*: $P_{\text{Fusion}} = 3.0 \Rightarrow 2.7\text{GW}$ (-10%).

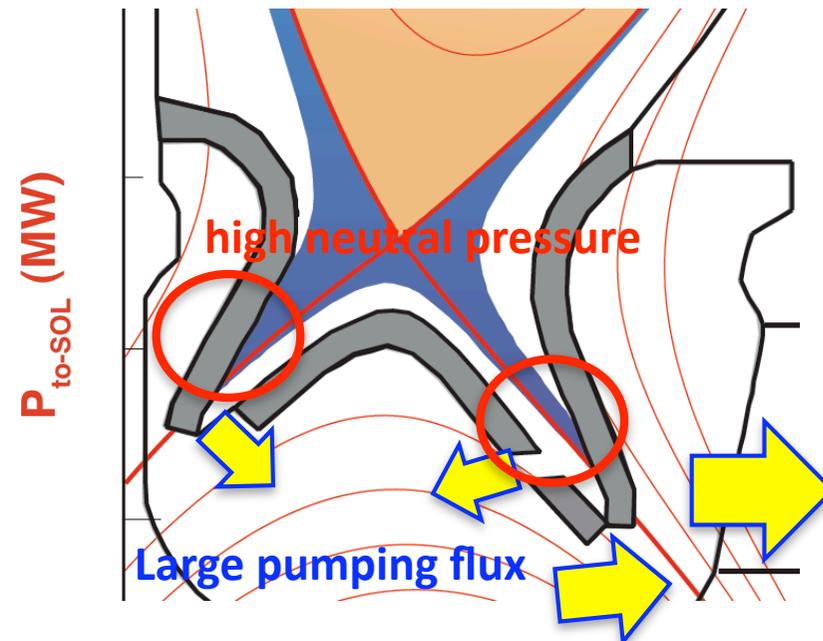
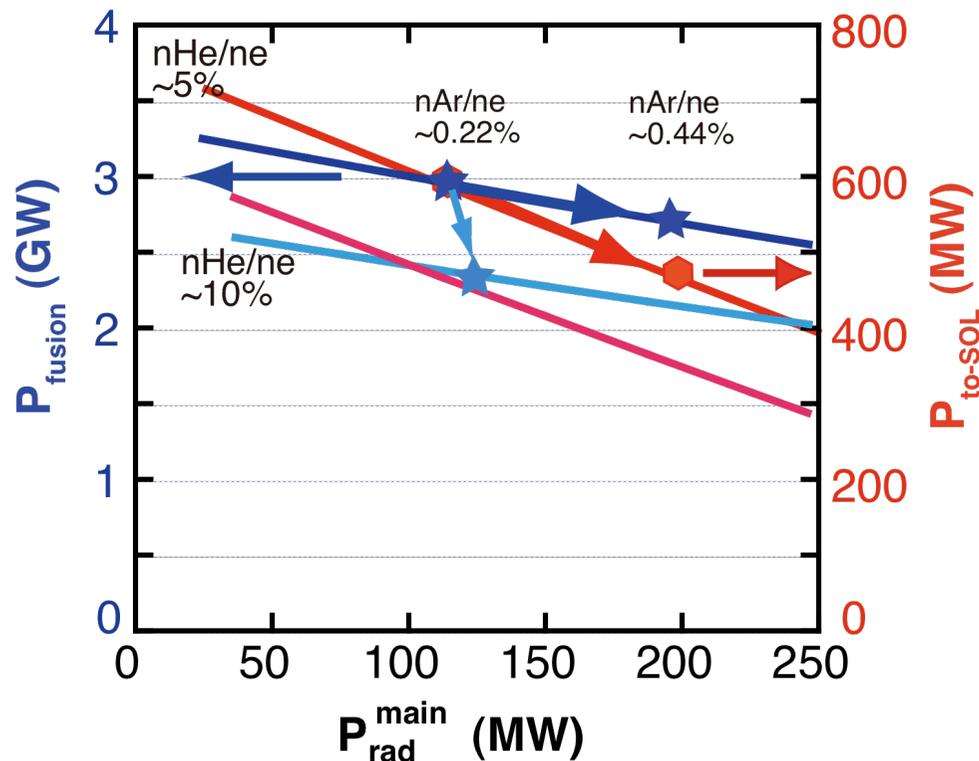
He concentration ($n_{\text{He}}/n_e=5 \Rightarrow 10\%$) largely reduces $P_{\text{Fusion}}=3.0 \Rightarrow 2.2\text{GW}$ (-27%)

He exhaust is another important issue.

- Particle control, i.e. geometry and pumping speed, impurity seeding, should be determined to optimize the “divertor performance”,

He exhaust requires divertor pumping

↔ **Divertor detachment is formed under high neutral pressure and radiation loss.**



6. Issue for Plasma Facing Component (W-PWI)

Tungsten is foreseen as PFCs (divertor and first wall) in DEMO reactor.

PSI properties have been investigated for application of the ITER divertor.

Following W-PWI issues/database should be focused under the high fluence:

- (1) “bubbles”, “holes”, “nano-structure” formation by He ion irradiation at $T_w > 700^\circ\text{C}$
- (2) Neutron irradiation effects : defect, blistering, increasing DBTT and T-retention.
- (3) Target design/arrange of mono-block armors and melt-layer dynamics.

Their dependence/threshold on temperature and fluence and energy are investigated in recent experiments under the ITER-level condition.

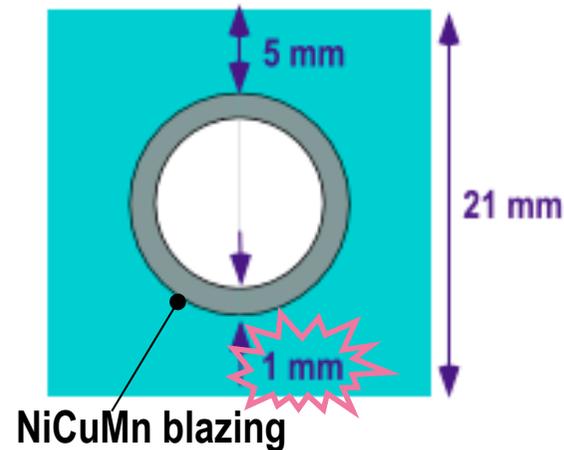
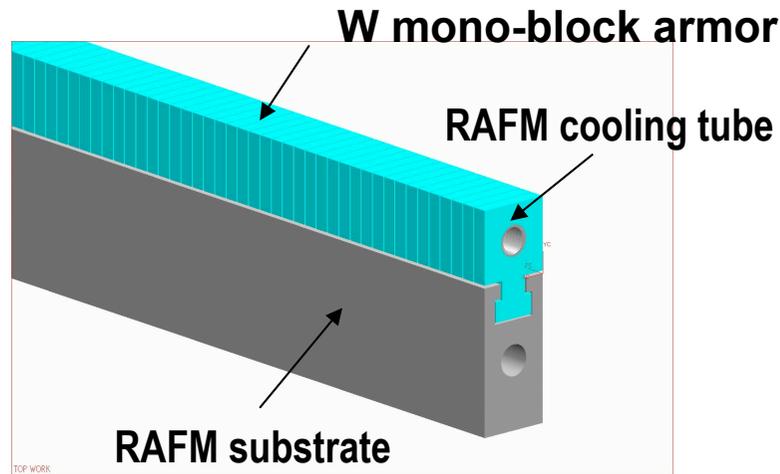
On the other hand, **fluences of D/T/He ions and neutrons in DEMO reactors are far beyond existing database.**

	ITER (1 shot)	DEMO (continuous)
T_w at SS ($^\circ\text{C}$) water-cool	~ 1000 [base 100-200]	< 1200 [base 290]
T_e near strike-point (eV)	1-30	1-20
Fuel ion fluence (m^{-2})	$5 \times 10^{25} - 5 \times 10^{26}$ (400s)	$10^{30} - 10^{31}$ (~year)
He ion fluence (m^{-2})	$10^{24} - 10^{25}$ (400s)	$10^{29} - 10^{30}$ (~year)
Neutron fluence (dpa)	~ 0.5 (~5 year)	20-100 (~year)

5. Issue for heat load handling: target heat sink

Tungsten is foreseen as candidate for the high temperature PFC in DEMO reactor: low sputtering yield & high energy threshold and low T-retention.

Heat removal is expected to 1/2 of ITER divertor since lower thermal conductivity of RAFM (F82H: 1/10 of Cu) and higher temperature water (200 °C at the inlet).



Divertor	ITER	DEMO
Cooling tube	Cu-alloy (CuCrZr)	RAFM
Armor	CFC/W	W
Coolant	water 100°C, 4MPa	water 200°C, 10MPa
Heat load	≤ 20 MW/m ²	≤ 10 MW/m ²

← Thermal conductivity 1/10 of Cu

← 1/2 of ITER Handle power of x6

↑ Ultimate design w/o margins!

Issue for heat load handling: target heat sink

(1) Higher base temperature $T_{\text{base}} \sim 290^\circ\text{C}$ (10MPa, 10 m/s) is required:

- Irradiation embrittlement at low temperature ($<300^\circ\text{C}$) may occur (few database).
- $T_{\text{base}} > 240^\circ\text{C}$ to avoid corrosion by radiation-produced hydrogen peroxide (H_2O_2)
- Sub-critical & Super-critical water ($>20\text{MPa}$) leads to enhance corrosion of RAFM.

(2) Allowable heat flux is reduced to 5-7 MW/m² K. Tobita, et al. Nucl. Fusion 49 (2009) 075029

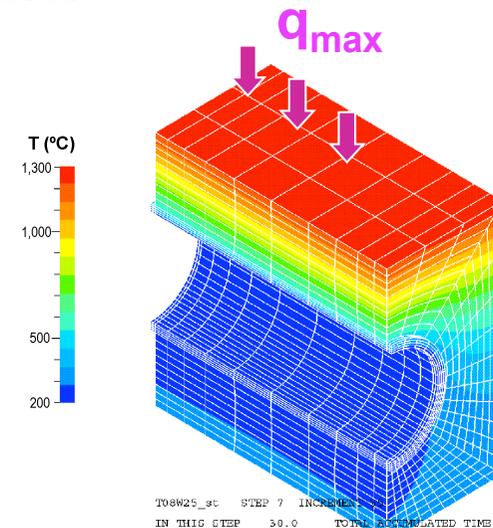
(2-1) allowable heat flux determined by thermal analysis:

$$q_{\text{max}} \sim 7 \text{ MW/m}^2 \quad (T_{\text{coolant}} = 290^\circ\text{C})$$

	Requirement
W	$T \leq 1,200^\circ\text{C}$
RAFM	$290^\circ\text{C} \leq T \leq 550^\circ\text{C}$

Recrystallization

Stress-creep



(2-1) allowable heat flux determined by thermal stress at F82H cooling pipe:

$$q_{\text{max}} \sim 5 \text{ MW/m}^2$$

Primary (pressure) + Secondary (thermal) Stress $< 3S_m$ (t 1mm F82H)

Possible to increase the thickness to $\sim 2\text{mm}$ if allowed to use F82H above 550°C