Power exhaust simulation for the SlimCS divertor with the SONIC code

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1. Introduction

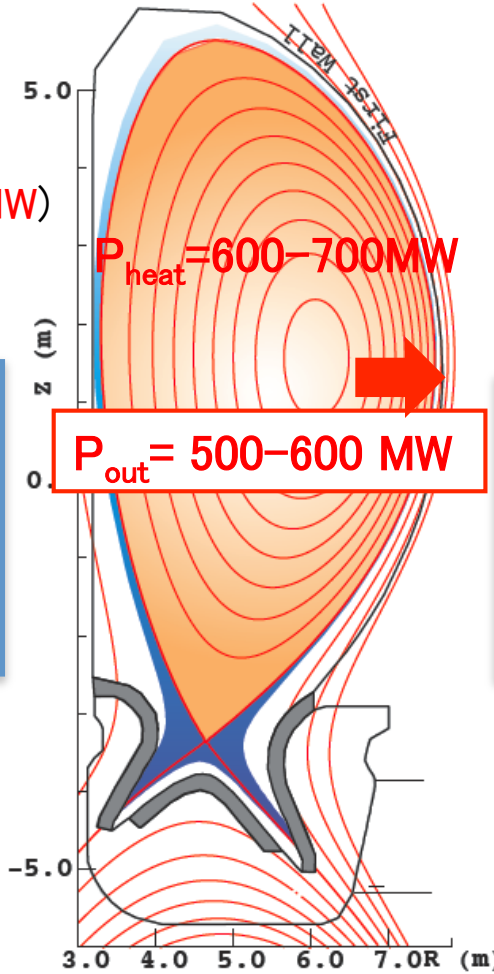
- "***SlimCS***" aims P_{fus} ≤3 GW (P_{heat}= 600~700 MW) with A=2.6 and reduced-size CS.
  ⇒ Power exhausting to SOL is 5-6 times larger and R is smaller than ITER.
  Power handling by plasma operation, divertor design, and target engineering is the most important issue for the reactor design.

SlimCS

P_{fusion} = 2.95 GW
(P_{heat}=P_{α}+P_{ax}=600~700 MW)

P_{out} = 500–600 MW
P_{rad}= 450 ~ 550 MW
2xP_{target} < 50 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 m^3

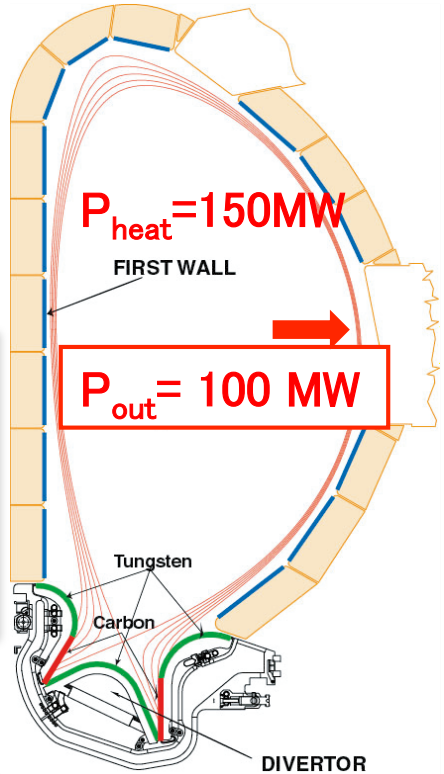


ITER

P_{fusion} = 0.5 GW
(P_{heat}=P_{α}+P_{ax}=150 MW)

P_{out} = 100 MW
P_{rad} ~50 MW
2xP_{target} ~ 50 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 m^3



Divertor concept for ITER and DEMO reactors

Power handling in *SlimCS* divertor was studied using SOLDOR/NEUT2D code⇒SONIC

Design concept for the ITER divertor is applied/extended to the DEMO divertor:

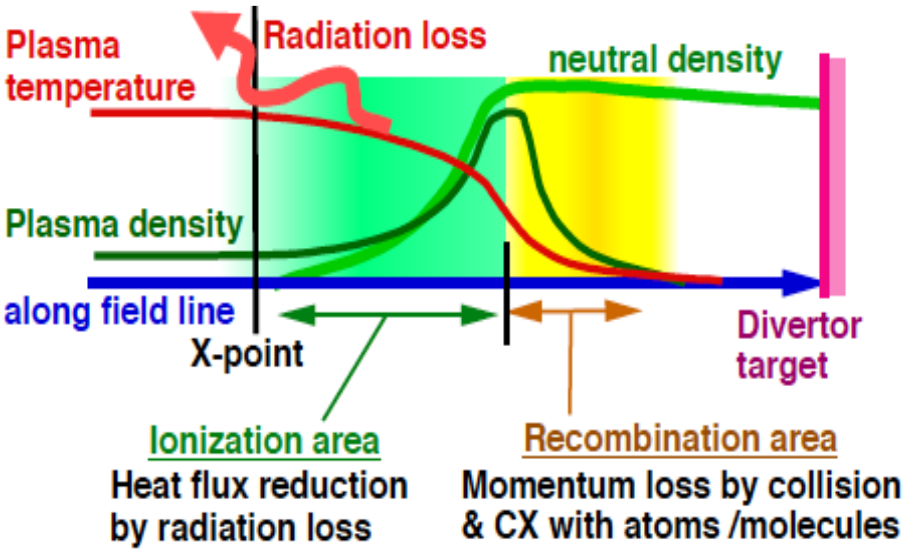
"divertor detachment" (T_e~ a few eV) is a key for the power handling

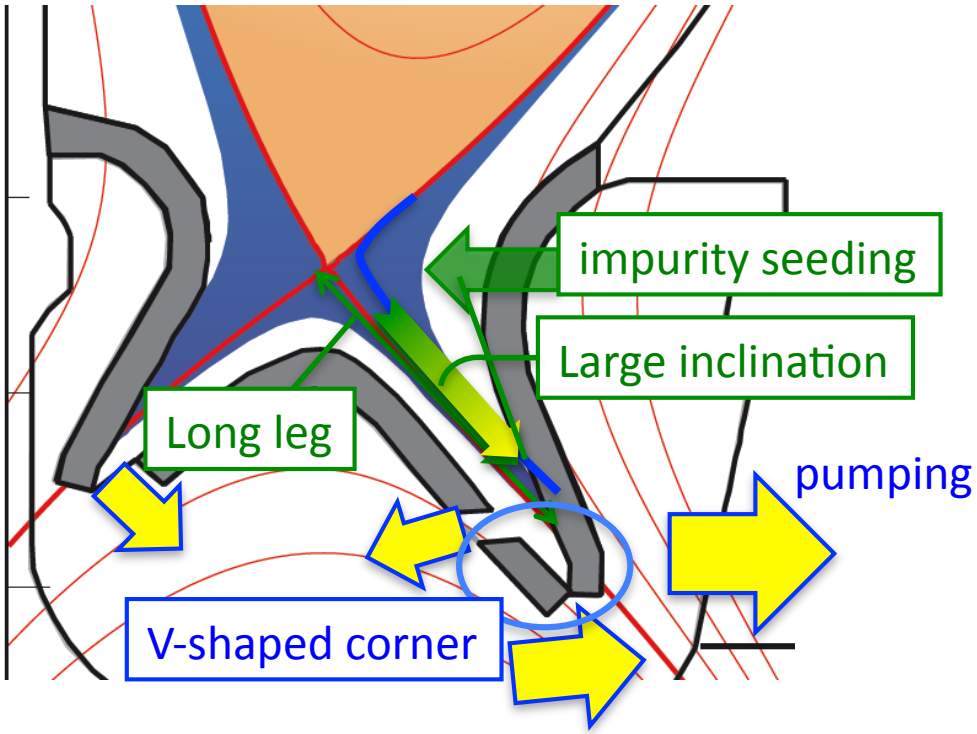
(1) Divertor leg and **inclination of the target** are larger than ITER

⇒ increase radiation, CX & volume recombination at the upstream, reducing q^{target}.

(2) V-shaped corner ⇒ enhance recycling near the strike-point.

(3) impurity seeding such as Ar (Ne, N_2, Kr, Xe) ⇒ enhance edge & divertor radiation.

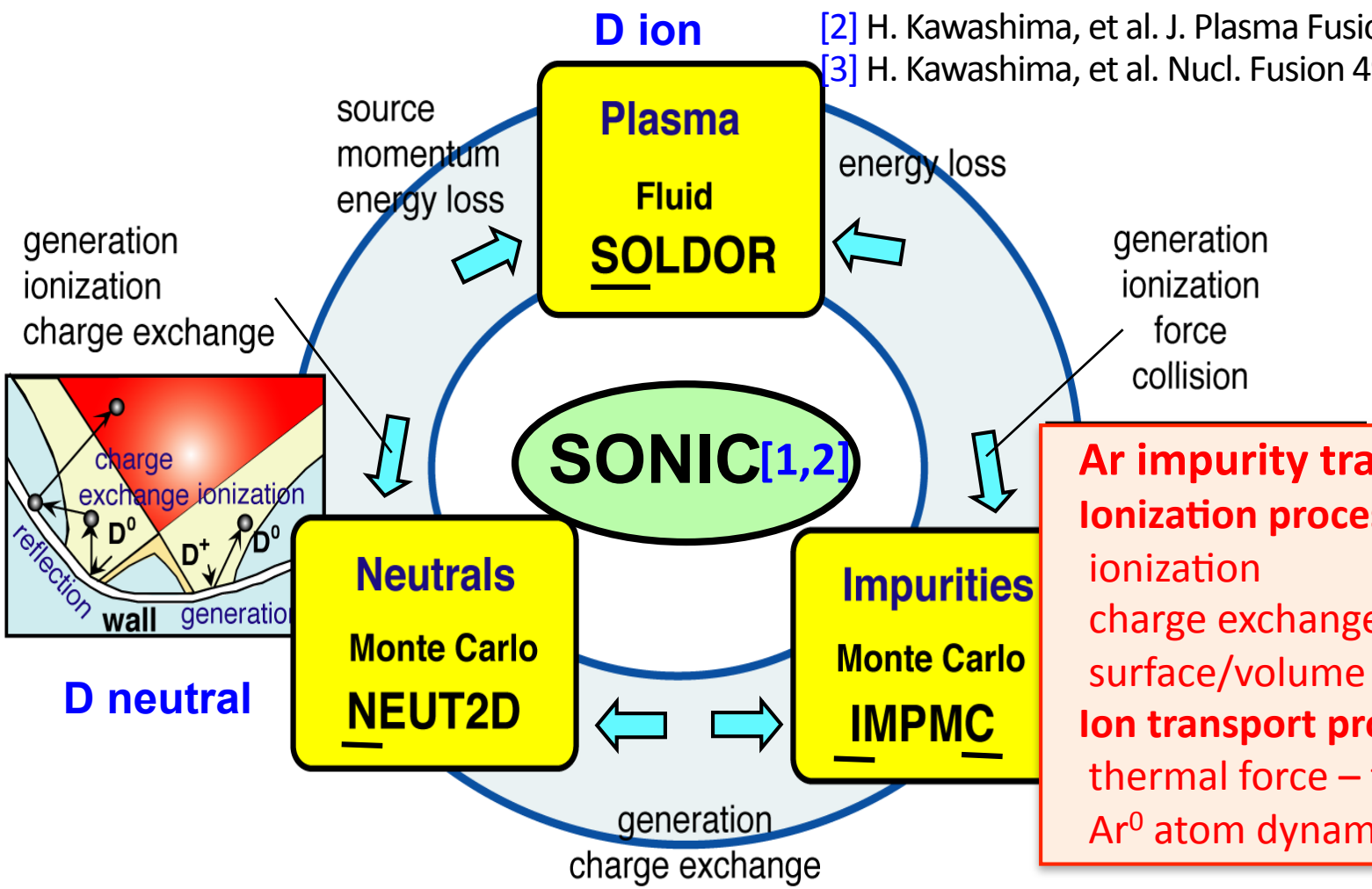




SONIC: self-consistent coupling with Ar impurity Monte Carlo has been developed for Ar seeding and transport

- 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) 1277
[2] H. Kawashima, et al. J. Plasma Fusion Res. 1 (2006) 31
[3] H. Kawashima, et al. Nucl. Fusion 49 (2009) 065007



Ar impurity transport

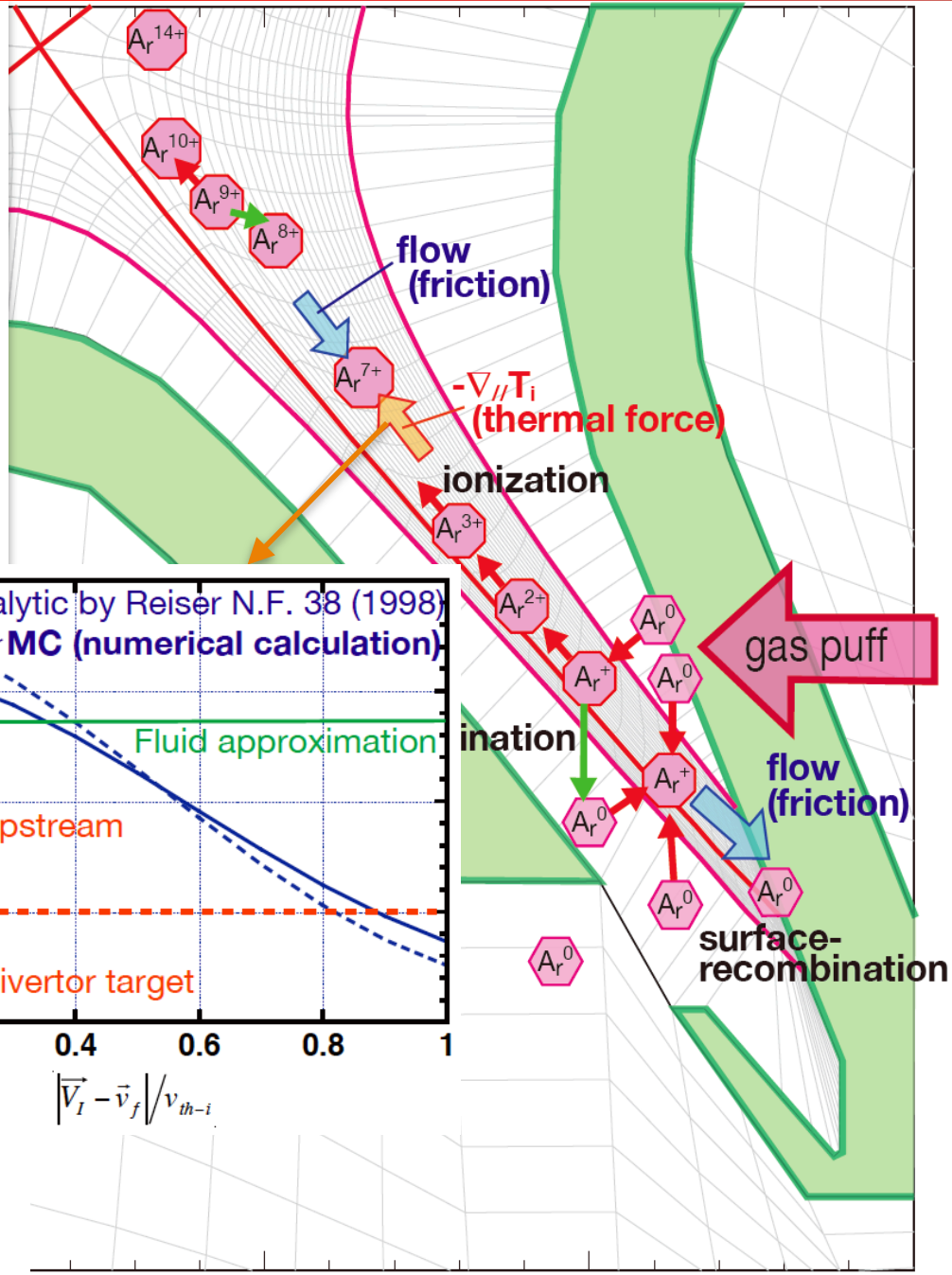
Ionization processes:
- ionization
- charge exchange
- surface/volume recombination

Ion transport processes:
- thermal force – friction force
- Ar^0 atom dynamics

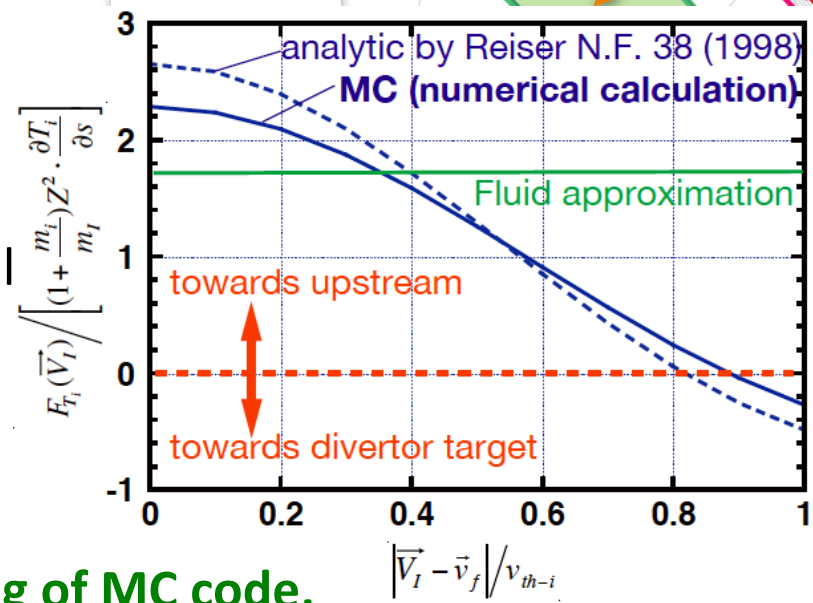
MC approach has advantages to impurity modelling

Most impurity transport processes are incorporated in original formula:

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



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



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

2. Simulation of power handling in the SlimCS divertor

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

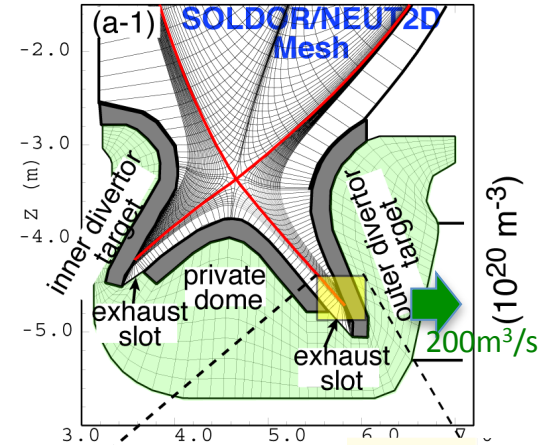
H. Kawashima, et al. Nucl. Fusion 49 (2009) 065007

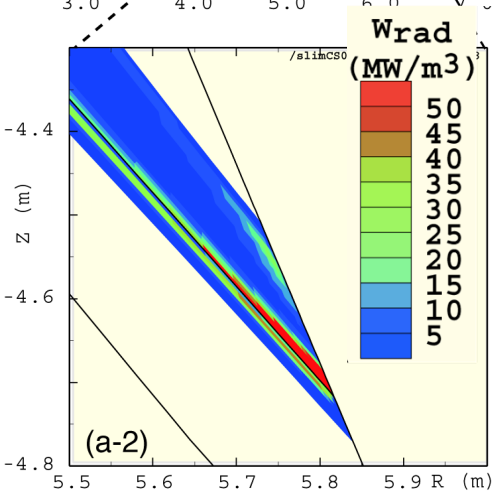
Input parameters at edge-SOL

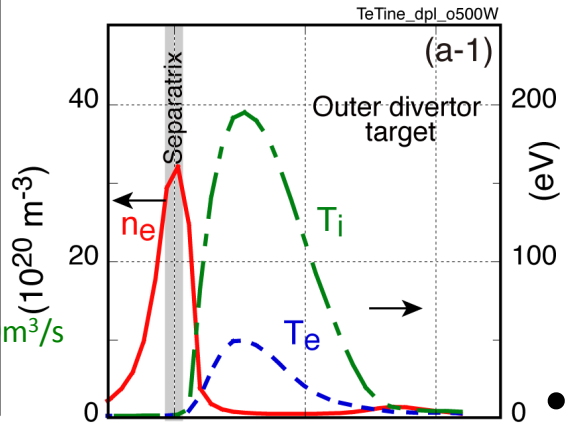
P_{out}= 500 MW, Γ_{out}=0.5x10^{23} s^{-1} (r/a=0.95)

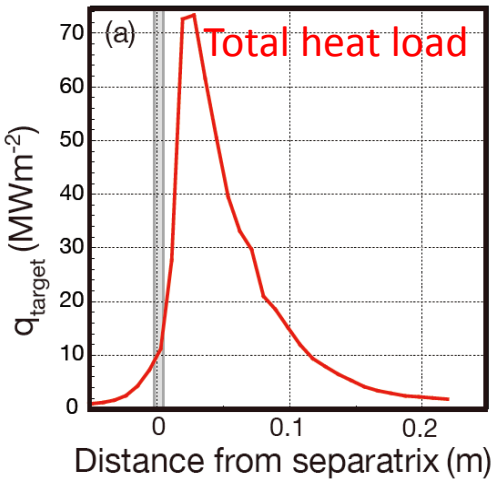
$\chi_i = \chi_e = 1$ m^{2}s^{-1}, $D = 0.3$ m^{2}s^{-1}

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









D_2/T_2 gas puff: Γ_{puff}=1x10^{23} s^{-1} (200 Pam^{3}s^{-1})

Ar fraction: $(n_{Ar}/n_i)_{o\text{-}div}$=2% , $(n_{Ar}/n_i)_{edge\text{-}SOL}$=1%

applying *non-coronal model*:$P_{rad} = L(T_e,\tau_r)\, n_z n_e$

Divertor pumping speed at exhaust duct:

S_{pump}= 200 m^{3}s^{-1} is given.

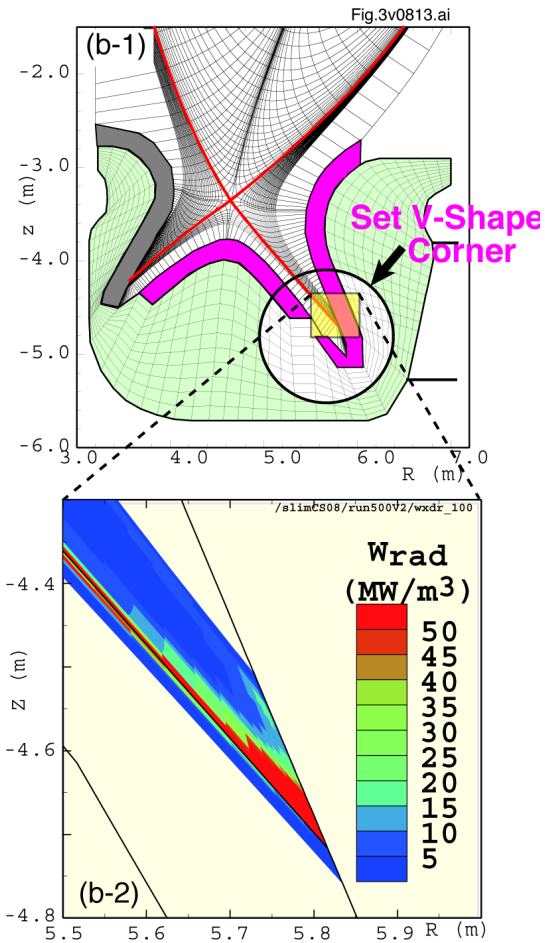
- At the inner target, divertor is detached and q^{target} < 5 MW/m^2.

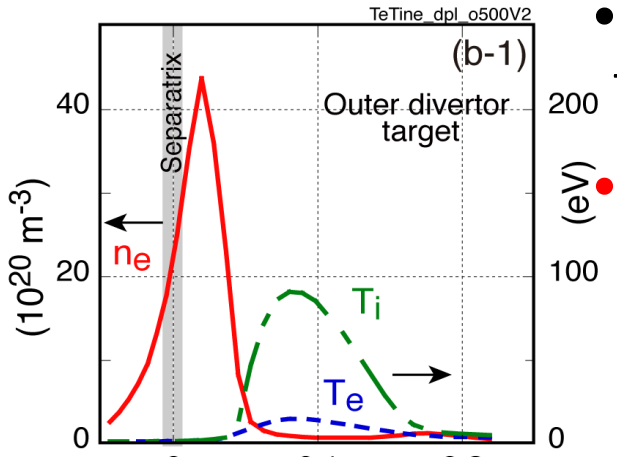
- At the outer target, high temperature at the strike-point:

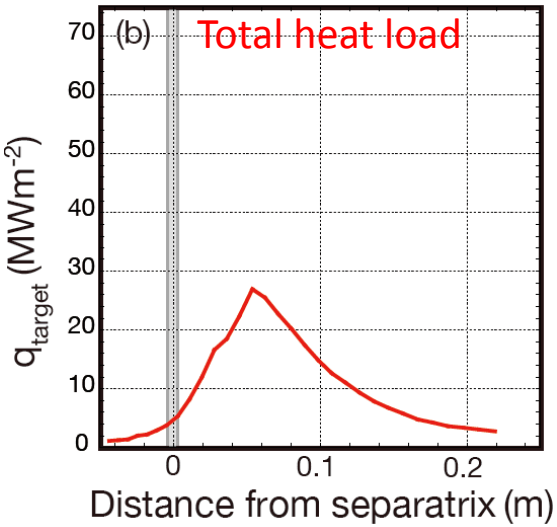
  peak T_e~50 eV and *T_i*~200 eV, giving **severe peak heat load ~70 MW/m^2 !**

2.1 Power handling in divertor: divertor geometry

Case-2: Concept for the ITER divertor, *V-shaped corner*, was investigated







- *Divertor recycling* is increased from 3.7×10^{24} to 4.2×10^{24} s^{-1}.
- *Radiation loss at the outer divertor* is increased at upstream of the strike point **from 85 to 142 MW**: Total P_{rad}*(edge+div.)* = 390 MW (P_{rad}^{edge}~130MW, P_{rad}^{div}~260MW)
- *Peak* T_e~20 eV ,T_i~90 eV are smaller by the factor of 1/2~1/2.5.

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

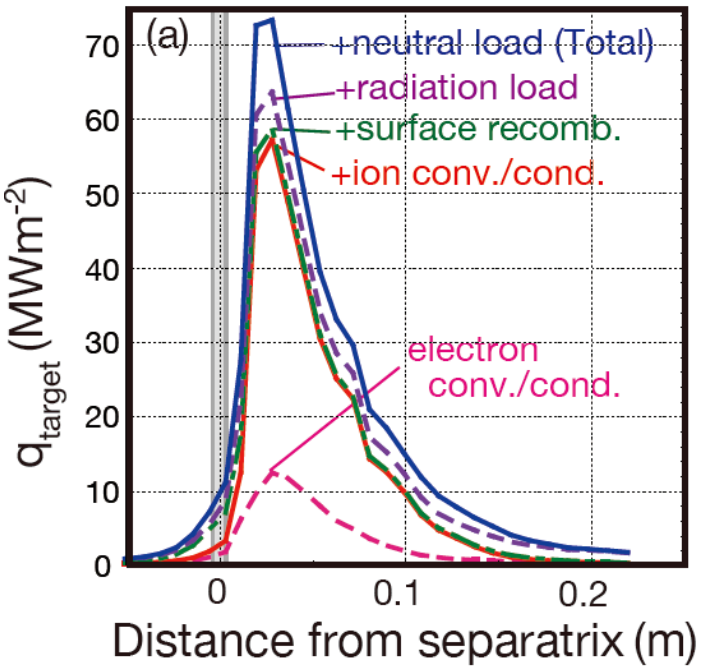
Peak heat load is reduced from 70 MW/m² to 27 MW/m².

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

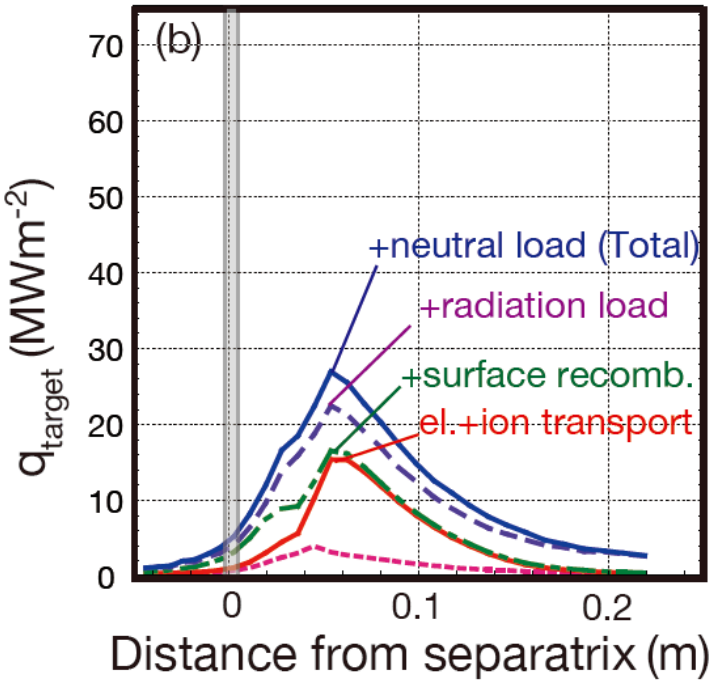
- **Evaluation of major heat load on the target**

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

Case-1:pumping from bottom corner



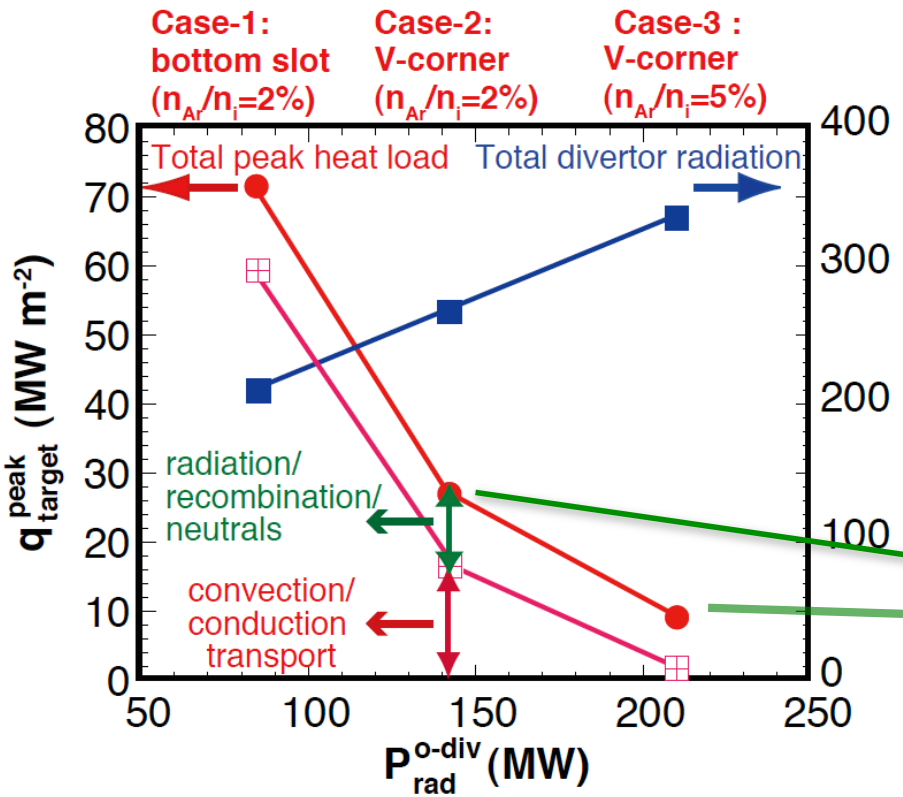
Case-2: "*V-shaped divertor*"



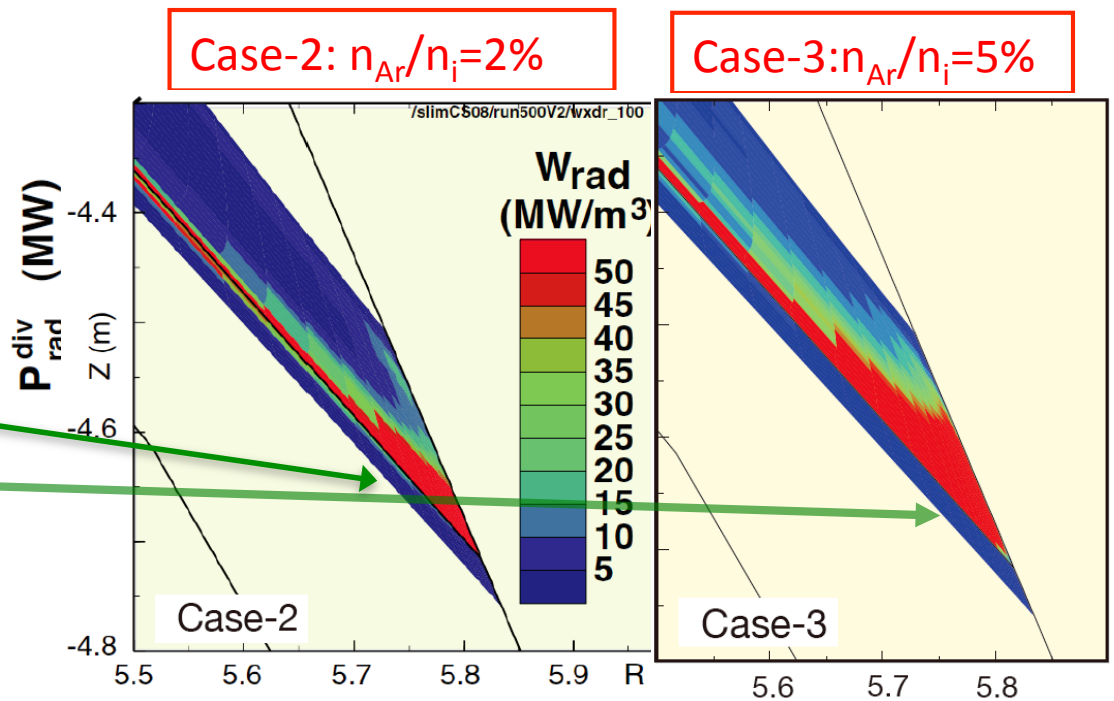
2.2 Power handling in divertor: increasing Ar seeding

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

- Large heat load extends in a wide divertor area, when P_{rad}^{tot}/P_{out} increased to ~92%: **Peak heat load in the detached divertor, q^{peak} ~ 9 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.

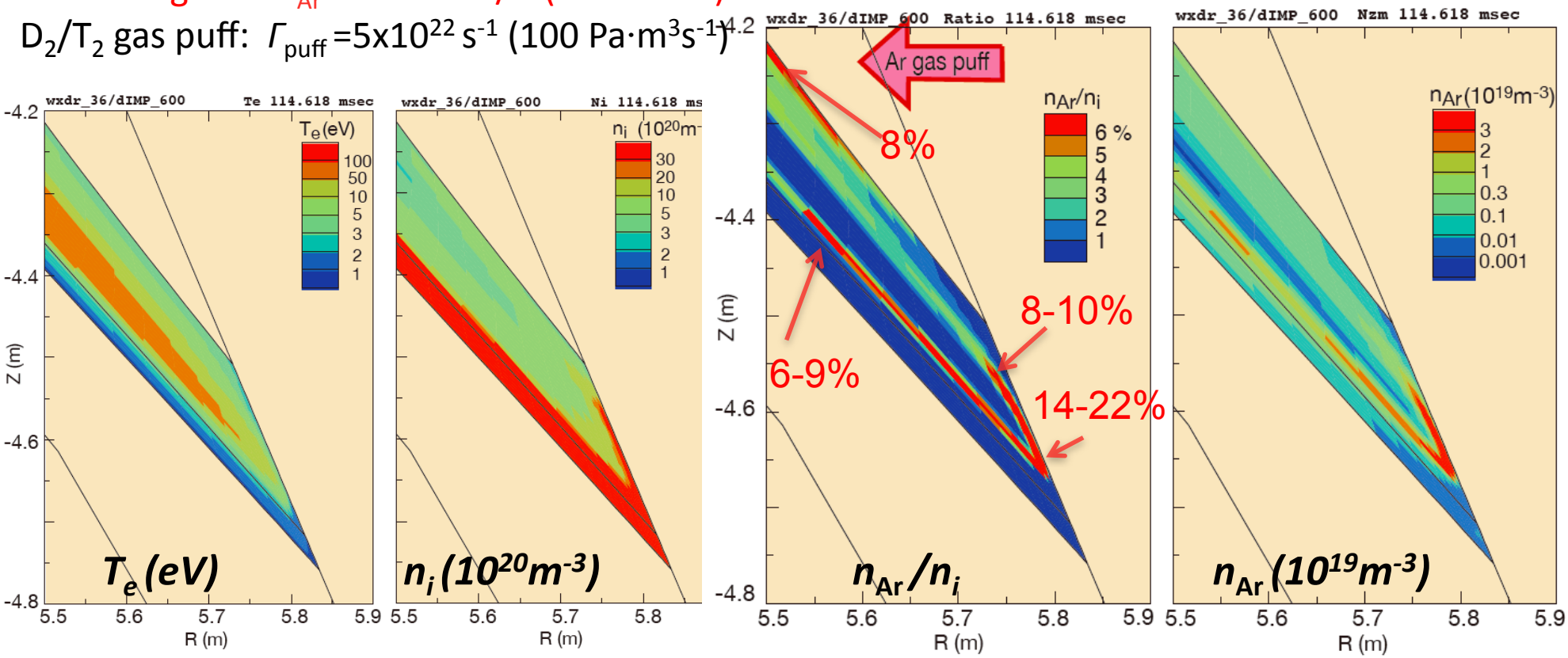
Ar transport was simulated till t ~ 30 ms (time scale of particle transport in divertor):

friction force by the plasma flow is dominant ⇒Ar recycling is enhanced near the target

⇔ Influence of ***thermal force*** on impurity transport is dominant **near the separatrix**

Ar seeding rate : Γ_{Ar} =2x10^{21} Ar/s (4 Pa·m^{3}s^{-1})

D_2/T_2 gas puff: Γ_{puff} =5x10^{22} s^{-1} (100 Pa·m^{3}s^{-1})



Detachment was different depends on initial condition of the divertor

Self-consistent solutions for P_{out} =500 MW, Γ_{Ar} =2x10^{21} Ar/s were obtained using **the different initial conditions**:

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

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

- Different divertor plasma profiles were sustained *after the time scale of particle transport in the divertor. They were still transient*.

IC-1: plasma from Case-2

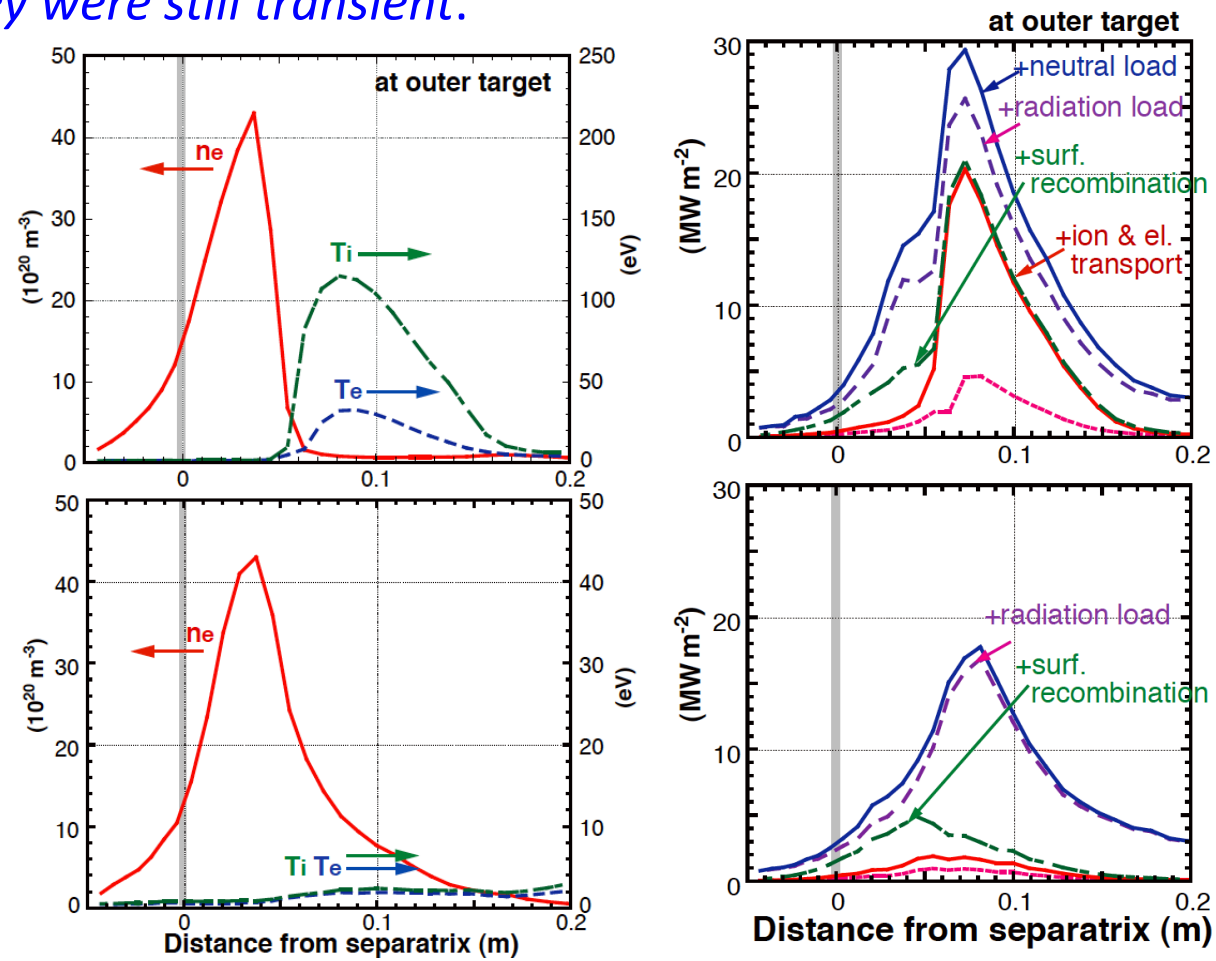
Detached near separatrix, and attached at the outer flux surfaces.

➔ max. q_{div} ~28 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} ~18 MWm^{-2}, where radiation power flux is dominant.



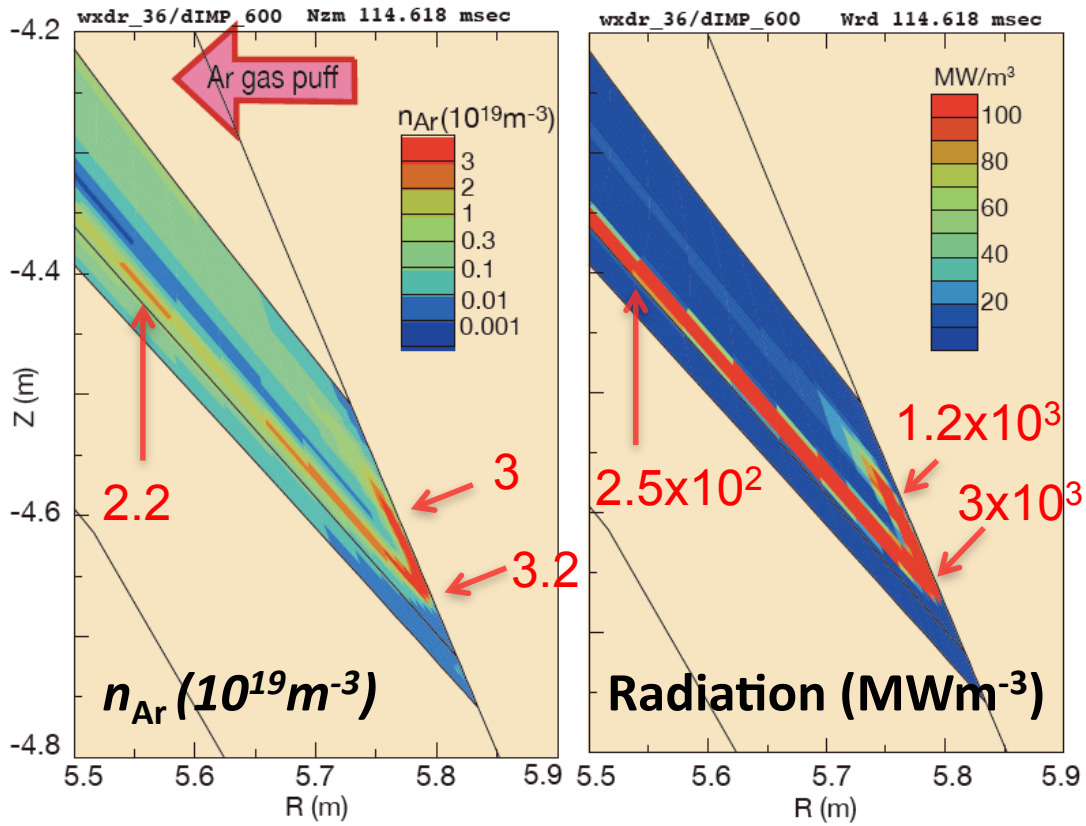
Radiation power load from MC modelling is dominant more than *Non-coronal model with Constant n_{Ar}/n_i*

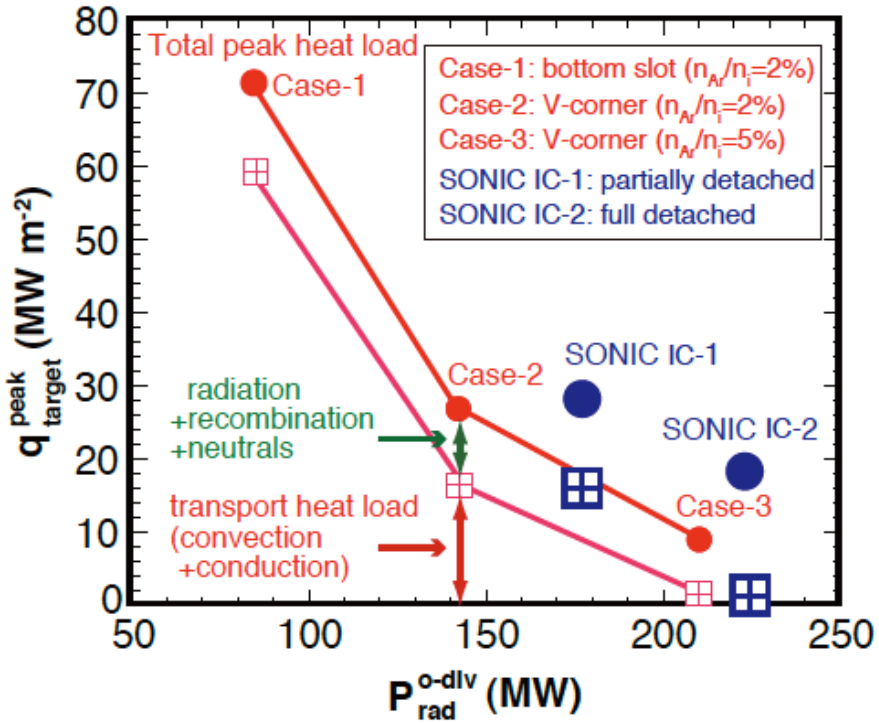
- Region with large radiation loss (> 100 MWm^{-3}) is localized just above the target, while the full detachment is sustained in the transport time scale (IC-2 case).
- Ar transport to the upstream SOL/edge is still transient:

radiation at SOL/edge, P_{rad}^{edge} ~ 20MW, is smaller than P_{rad}^{edge}~130MW (n_{Ar}/n_i ~1%)

➔ **Investigation of Ar transport and radiation power at upstream SOL/edge is necessary to determine appropriate or combination of the radiators.**

SONIC IC-2: full detached divertor case





4. Summary of power exhaust study for the DEMO divertor

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

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

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

⇒ Peak heat load q_{target}~9MW/m^2, which was attributed mostly to *radiation and neutral flux were 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 Monte-Carlo has been developed for 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 ~ 30 ms* (time scale of particle transport in divertor), *but still transient at the upstream SOL/edge*.

⇒ **Region with large radiation loss (>100 MWm^{-3}) is localized just above the target, while the full detachment is sustained in transport time scale in the divertor.**

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 simulation/modelling

- *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.

- Extension to the steady-state distribution (t~1s) will be investigated in IFARC parallel computer effective speed of 100TFlops (5000 times faster than JAEA: 20GFlops).
  Now, ~9 hours are required for SONIC calculation of 10ms (need 100 times more).
  ⇒ SONIC calculation in steady-state (1s) will be 0.2 hour!

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 influence of the divertor and degradation of core performance are investigated in P_{rad}^{tot}/P_{out} > 90%.
- Improvement of tentative target design (W, RAFMS, water-cooling) is 5-7MWm^{-2}.

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 (sturacture material) & water cooling, allowable heat flux is tentatively expected to 5-7 MW/m^2.

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

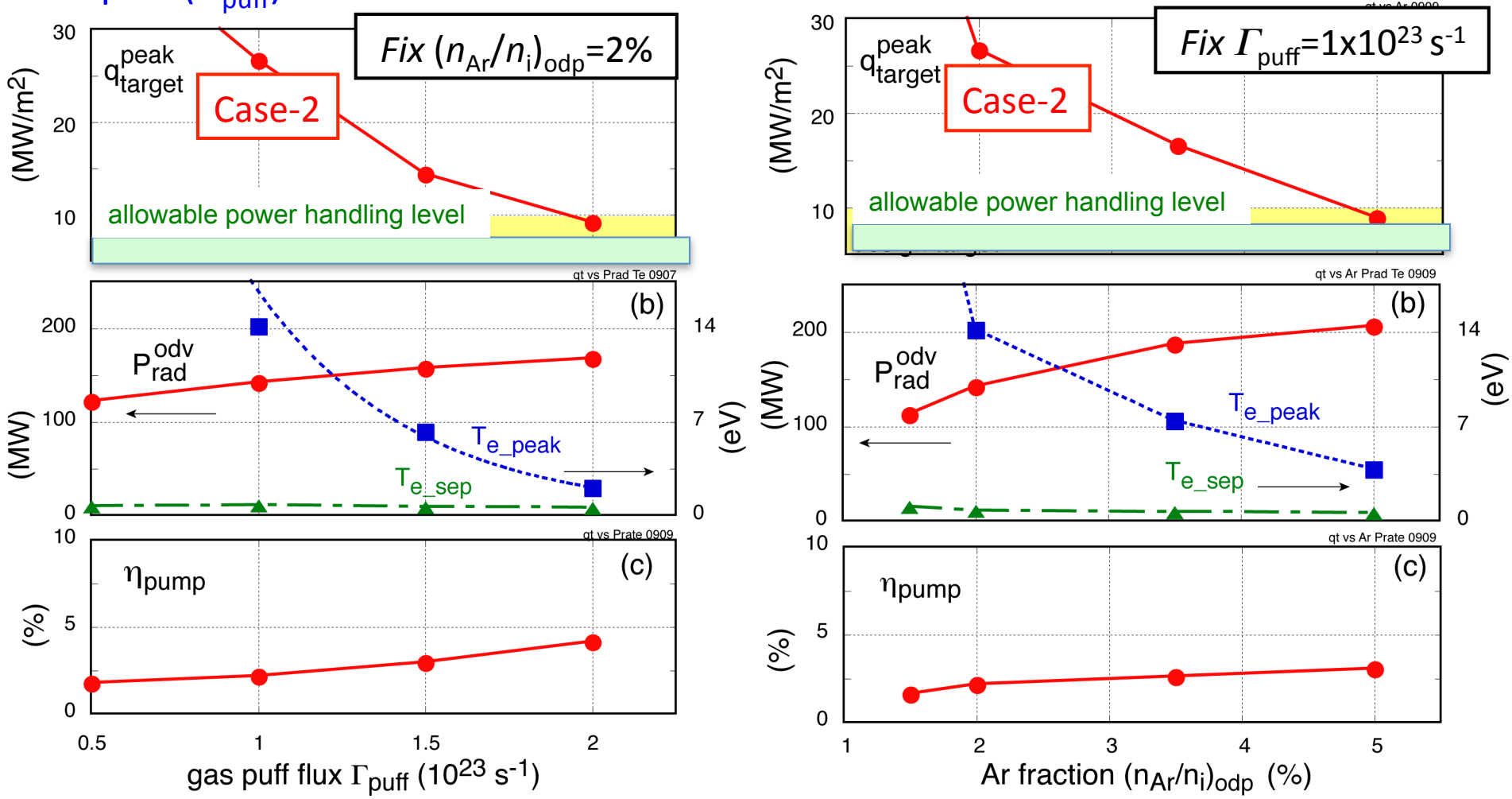
On the other hand, **fluences of D/T/He ions and neutrons in the DEMO reactors-level** are far beyond existing database.

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

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

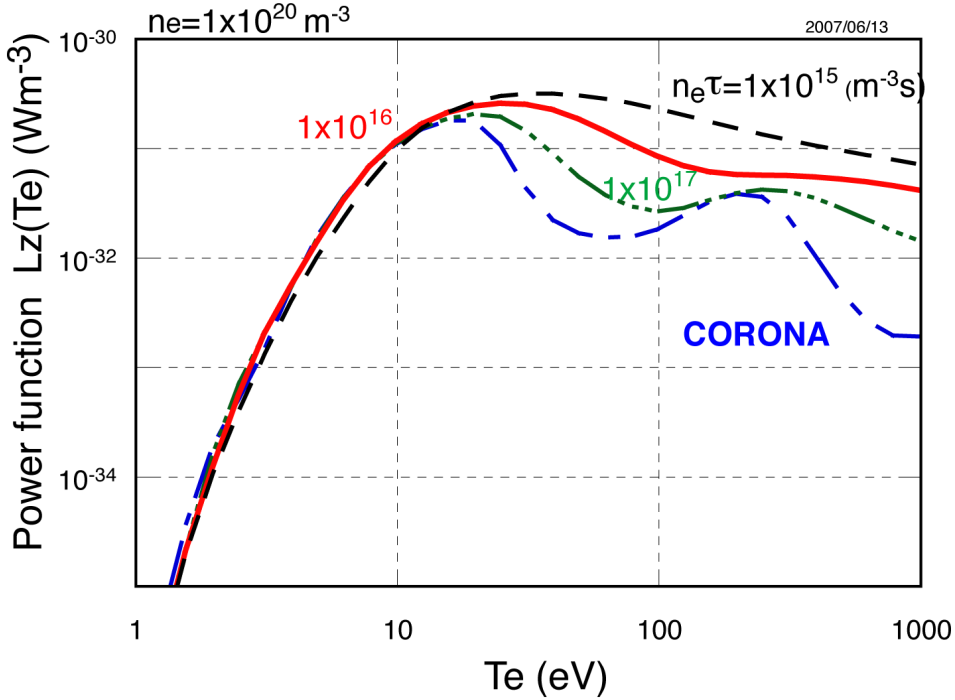
- Gas puff (Γ_{puff}) is increased to 2x10^{23} s^{-1}

Ar fraction is increased to $(n_{Ar}/n_i)_{odp}$ =5%



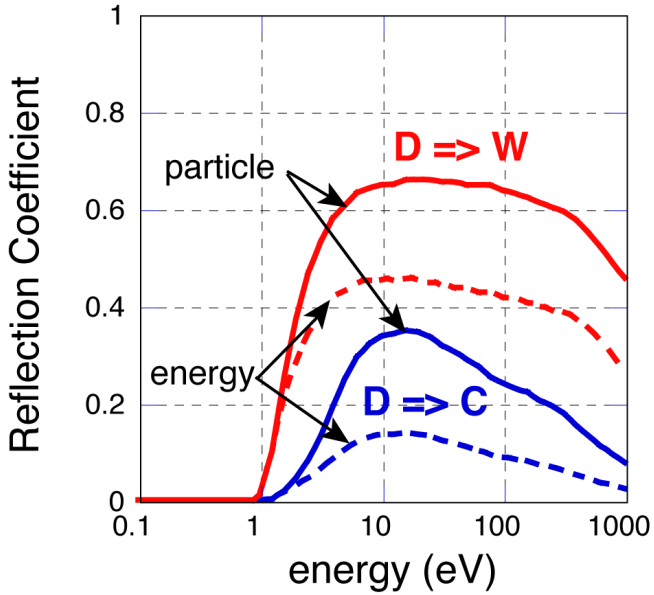
- Pumping rate η_{pump} is increased from 2% to 3-4% by increase the neutral density.

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 $n_e \tau_{res}$=1x10^{16} s/m^3.

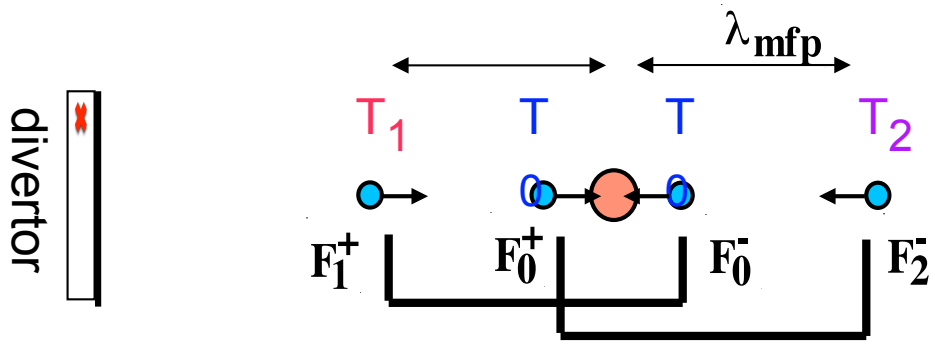


Neutral reflection: W target model

- 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.



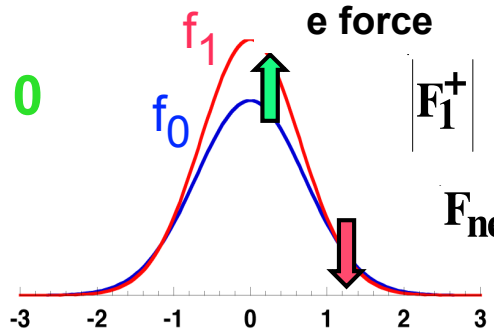
$T_1 < T_0 < T_2$

$F_{T_i}(V_0) \propto \int dv\, df_i(v)\, m_I \{Dv_{//}\}_i$

$F_0^+ + F_0^- = F_{v_f}$

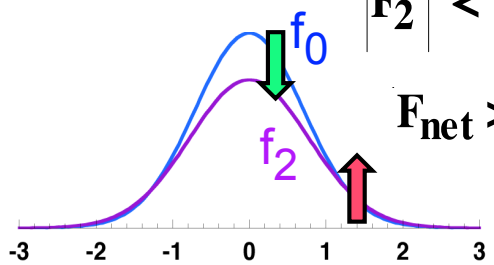
composite force

$V_0 \sim 0$



$|F_1^+| > |F_0^-|$

$F_{net} > 0$



$|F_2^-| < |F_0^+|$

$F_{net} > 0$

$V_0 \sim v_{thi}$

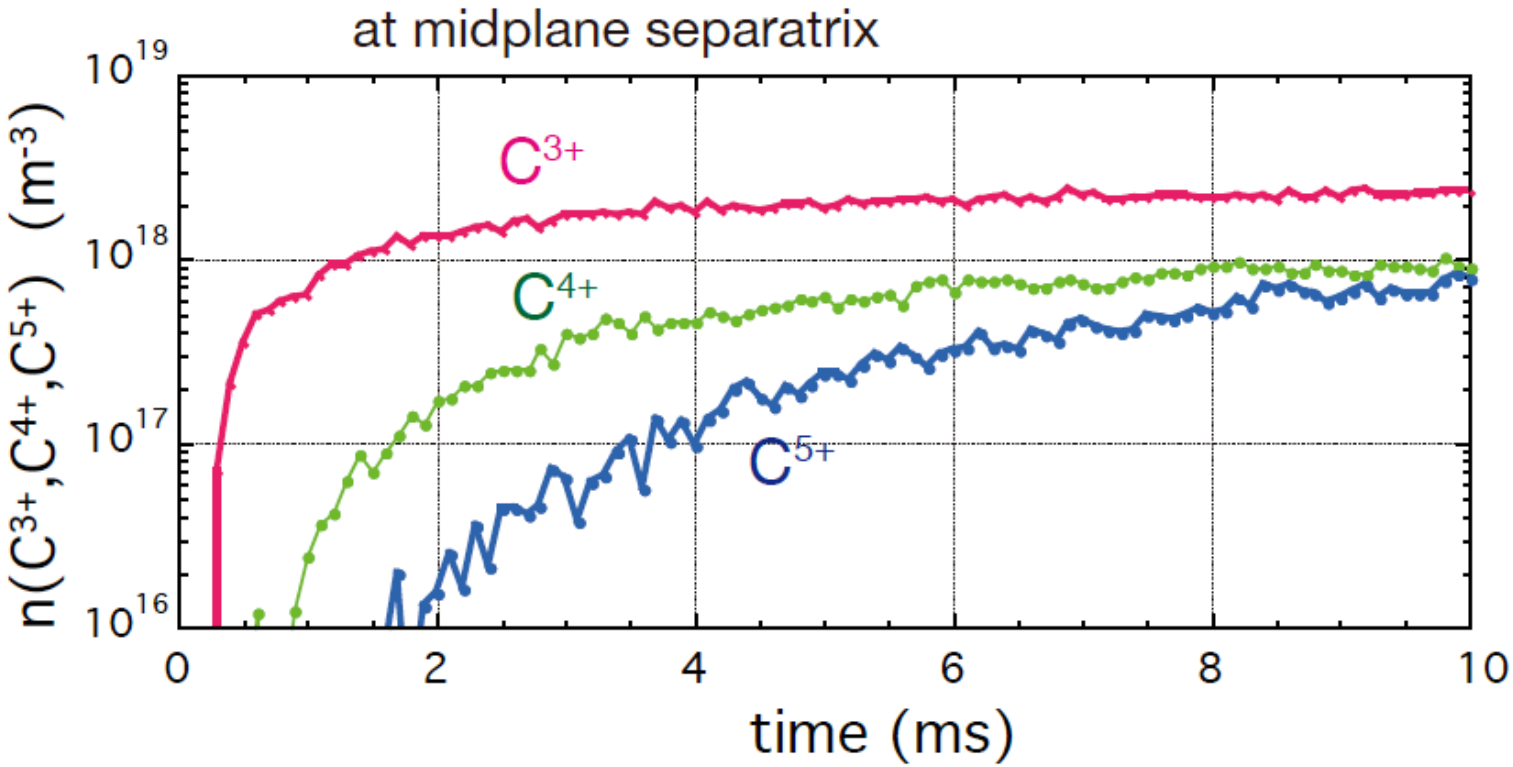
$|F_1^+| < |F_0^-|$ $F_{net} < 0$

$|F_2^-| > |F_0^+|$ $F_{net} < 0$

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)

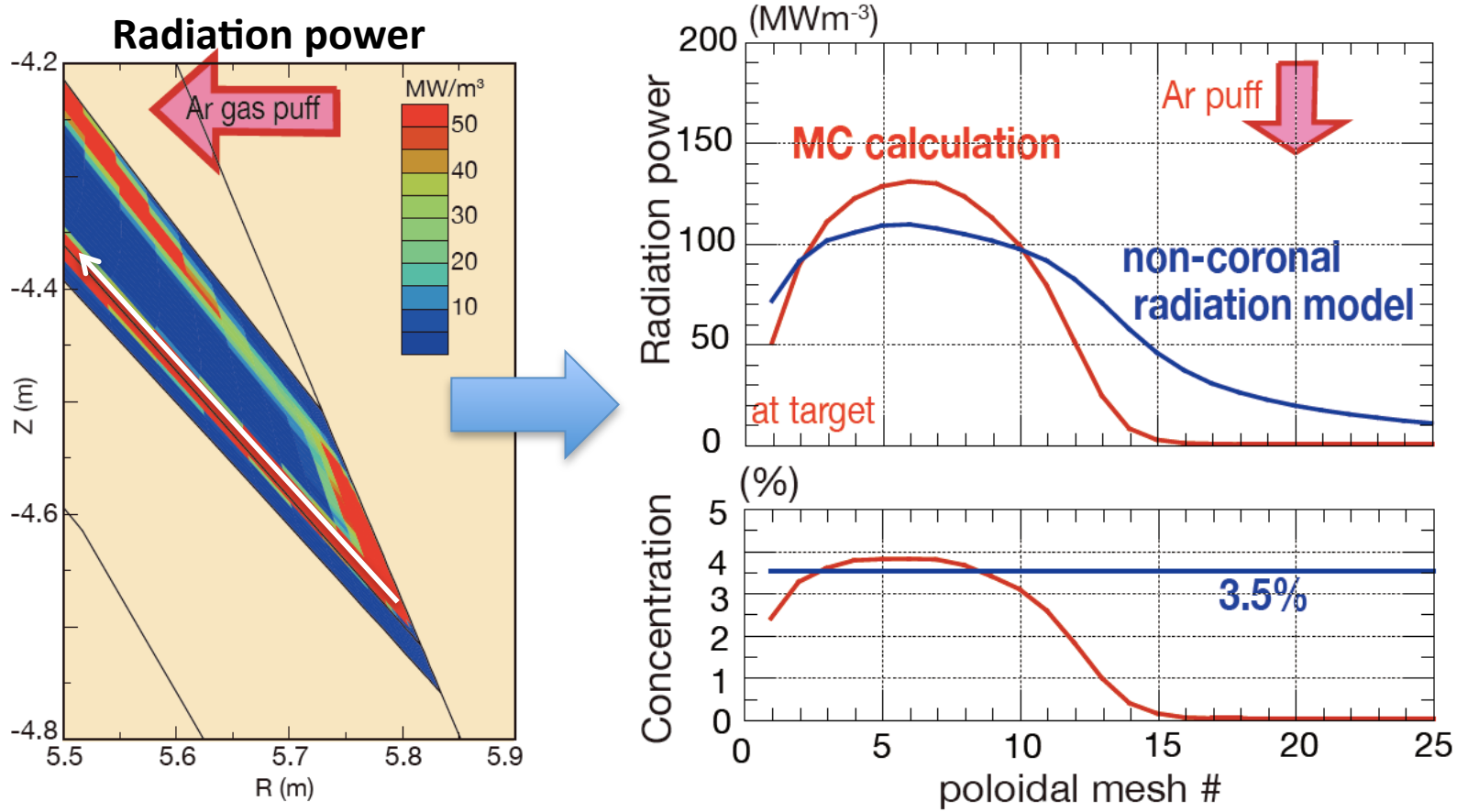
- Conversion of Carbon MC calculation was determined by impurities with higher charged-state.



Radiation profile (MC result) was localized above the target

- Radiation loss in the outer divertor was increasing during the MC calculation:
  $P_{rad}^{o\text{-}div}$ = 126 MW at t = 10 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 $(n_{Ar}/n_i)_{odiv}$ = 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_{Ar}/n_e=0.22 ⇒0.44%) reduces *Power to SOL* ($P_{to\text{-}SOL}$ = 600 ⇒ 480MW), with expense of *lowering Fusion power*: P_{Fusion} = 3.0 ⇒ 2.7GW (-10%).

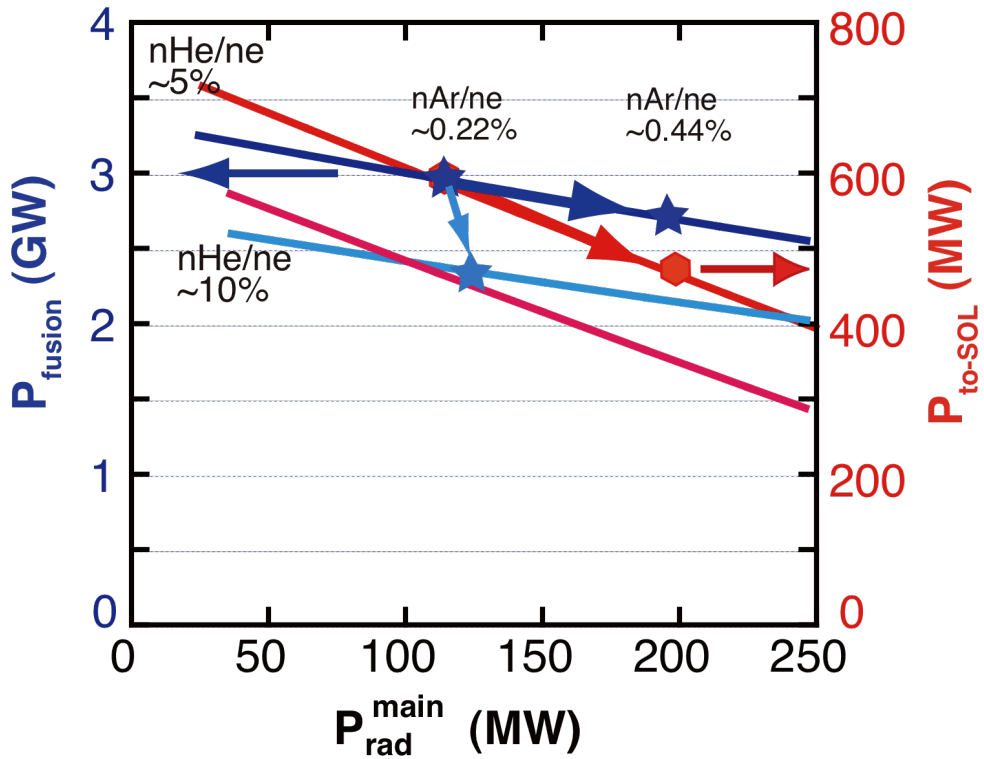
He concentration (n_{He}/n_e=5 ⇒10%) largely reduces P_{Fusion} =3.0 ⇒ 2.2GW (-27%)

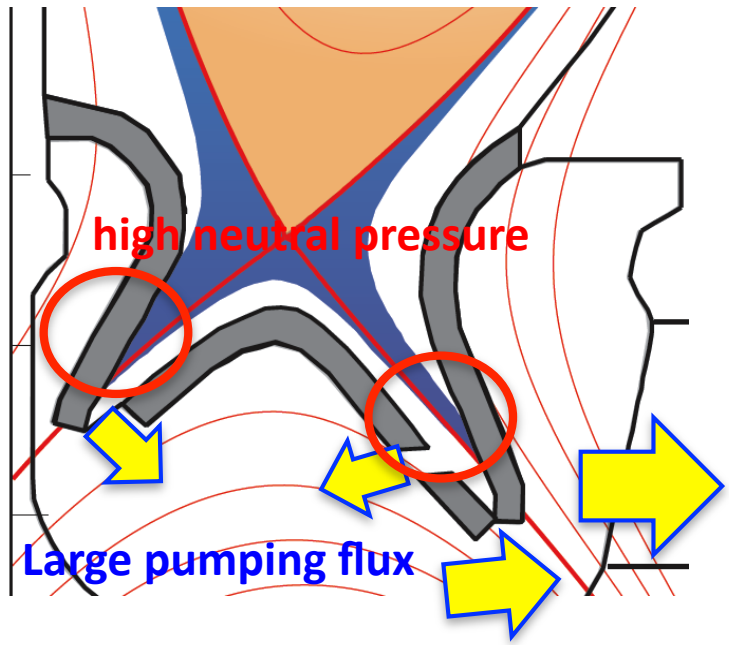
He exhaust is another important issue.

- **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°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 (°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})	$5x10^{25}$ - $5x10^{26}$ (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)