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Simulation studies of He and particle exhaust in detached divertor for JA DEMO design

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Contents

1. JA-DEMO design and power exhaust concept

Large power exhaust: P_{sep}/R = 30-35 MW/m, is required

Power exhaust concept of JA-DEMO design (JA-DEMO 2014)[1,2]:

System code predicted *Greenwald density* (n^{GW}: 0.67×10^{20} m^{-3}) is lower than ITER

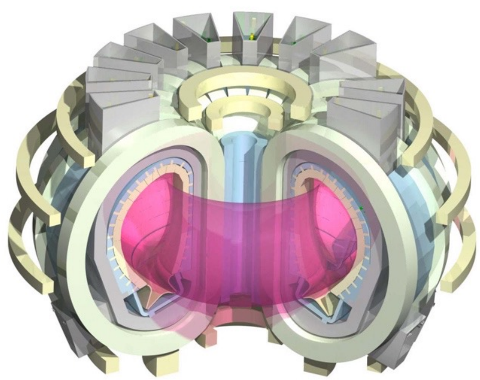
⇒ Impurity seeding is restricted up to n_{Ar}/n_e = 0.25% due to fuel dilution: to obtain Fusion power (P_{fusion} = 1.5GW) and Net electricity output ($P_{e\text{-}net}$ ~0.25GW), and β_N (3.5) and Bootstrap-fraction (0.6) with relatively high HH_{98y2} (~1.3).

JA-DEMO higher-κ proposal[3]: increasing κ_{95} from 1.65 to 1.75 for the same R_p, a_p, B_t and q_{eff}, which increases I_p (12.3 ⇒ 13.5MA) and n_{GW} (0.67⇒ 0.73×10^{20} m^{-3}).

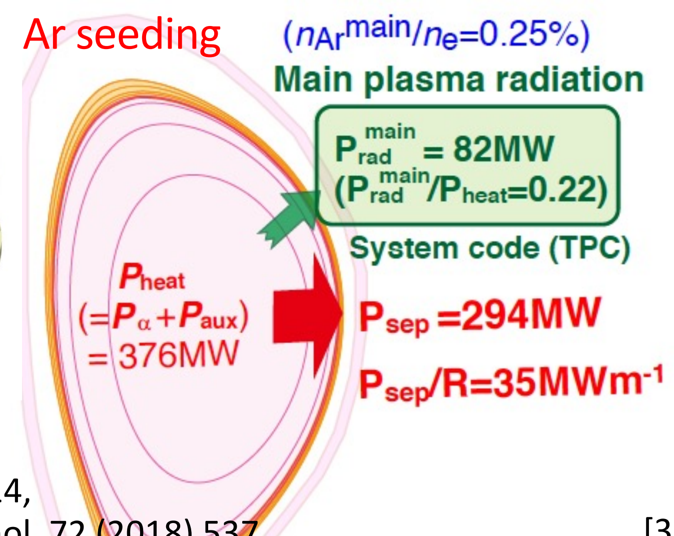
⇒ n_{Ar}/n_e and Radiation loss fraction ($f_{rad}^{main}=P_{rad}^{main}/P_{heat}$) are increased.

JA-DEMO 2014 B_t=5.9T, R/a=8.5/2.42m

I_p=12.3MA, κ_{95}=1.65, q_{95}=4.1, P_{fusion}~1.5GW

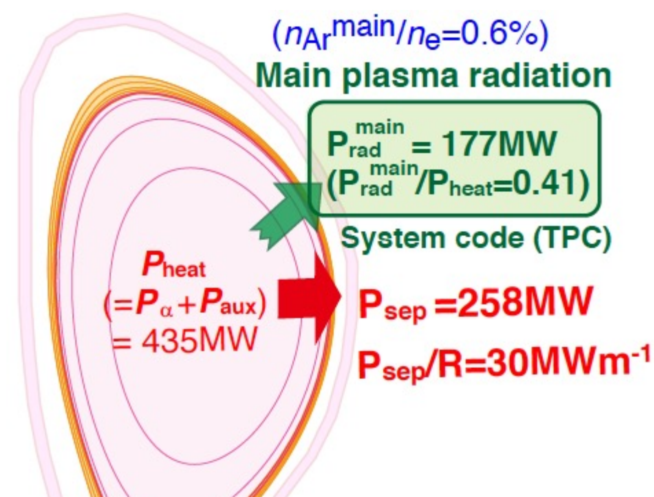


HH=1.3, β_N=3.4



JA-DEMO higher-κ proposal

I_p=13.5MA, κ_{95}=1.75, P_{fusion}~1.7GW



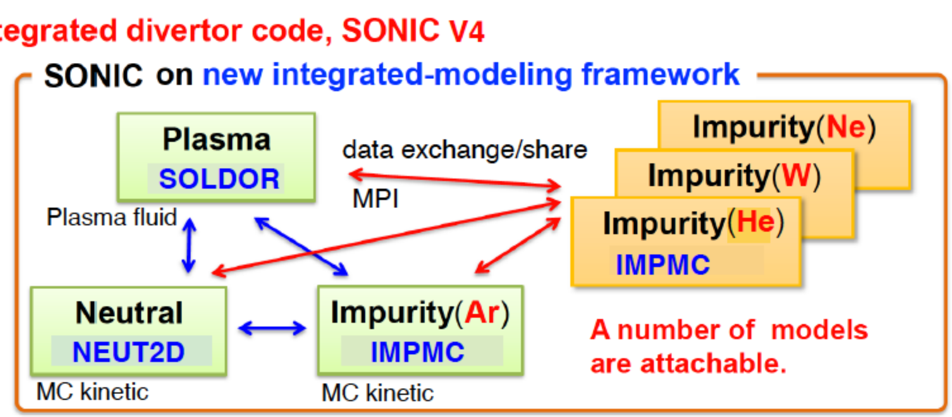
[1]Sakamoto, et al. IAEA FEC 2014,
[2]Tobita, et al. Fusion Sci. Technol. 72 (2018) 537
[3]Asakura, et al. Nucl. Fusion 57 (2017) 126050

Development of SONIC V4 and recent progresses

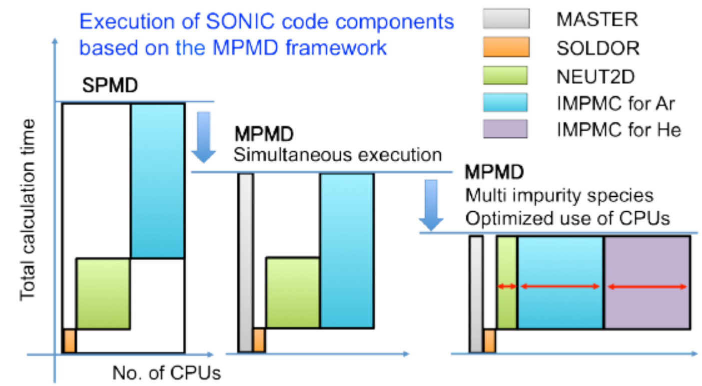
- **Modeling framework using MPMD (Multiple-Program Multiple-Data) approach and MPI (Message Passing Interface) data exchange scheme has been developed for**

(1) Each code can be independently developed, added and replaced.
(2) CPU number for each code can be adjusted to optimize performance.
⇒ **Plasma exhaust of DEMO divertor, incl. Ar and He transports, has been simulated.**

(1) Restructured SONIC code with MPMD framework



(2) Improved numerical efficiency for multi-impurity calculation



Recent progresses of modelling to evaluate following effects under the DEMO condition:

- **Kinetic models** (**thermal force on impurity transport** and **flux limiter for ion conduction**) **for low collisionality SOL in DEMO** were developed [4, 5].
- **Elastic collision model** of D-D, D-D_2, D_2-D_2, D-He is incorporated; **improvement in progress**[6]
- **Self-consistent photon transport simulation** was performed for SlimCS[7] and JA DEMO.

Introduction of drifts to SOLDOR is considered.

[4] Y. Homma, et al, Nucl. Fus.60 (2020) 046031, [5] Y. Homma, et al, Nucl. Fus.62 (2022) 045020.
[6] K. Hoshino, et al., PET-18 (2021) [7] K. Hoshino, et al., Contrib. Plasma Phys., 56 (2016) 657.

2. Influence of radiation loss and diffusion on power exhaust

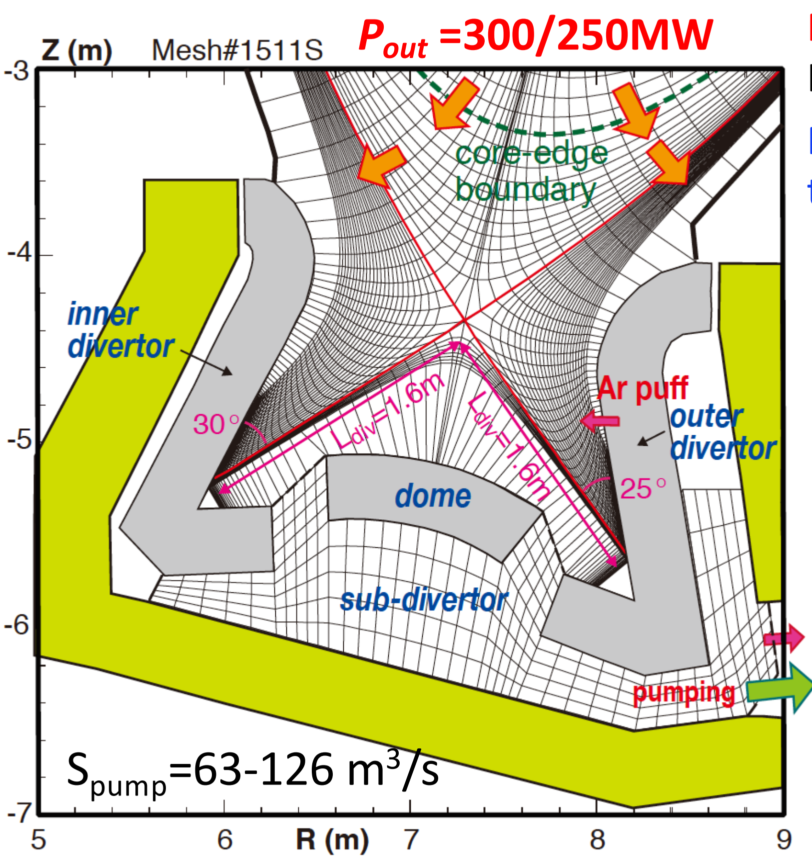
Divertor leg length: L_{div}=1.6m is proposed (x1.6 longer than ITER)

- P_{out}= 300 MW(DEMO 2014), 250MW(DEMO higher-κ) at core-edge boundary(r/a=0.95)
- SOL width 3.2 cm: covering connecting SOL between inner and outer divertors.

Operation window for $q_{target} \leq 10$ MWm^{-2} is determined in severe power exhaust params.:

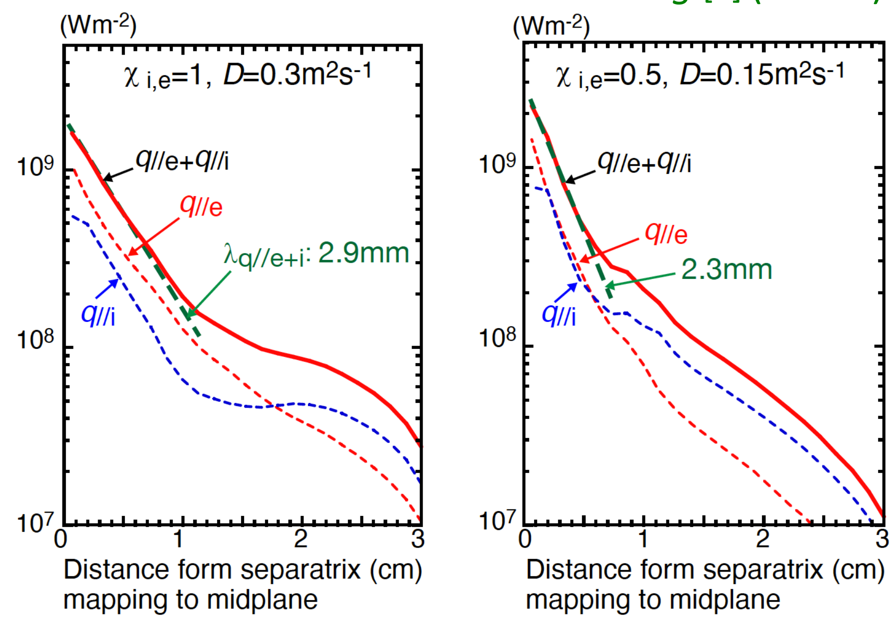
(1) Total P_{rad}/P_{out} is reduced from 0.8 ($f^{*}{}_{rad}^{div}=P_{rad}^{div+sol}/P_{sep}$~0.78) to 0.7 ($f^{*}{}_{rad}^{div}$ ~0.68).

(2) Diffusion coefficients are reduced from χ=1m^2/s & D=0.3m^2/s to half values.



For standard ITER χ/D=1/0.3 m^{2}s^{-1}: $\lambda_{q//e+i}$=2.9 mm (smaller than ITER case:3.4 mm [8]), where $q_{//e}$ is dominant near separatrix:.

Reducing to half values (χ/D = 0.5/0.15 m^{2}s^{-1}) ⇒ $\lambda_{q//e+i}$ is reduced to 2.3 mm: but still *wider than Eich's scaling* [9] (~1mm)



[8] Kukushkin, et al. J. Nucl. Mater. (2013). [9] Eich, et al. Nucl. Fusion (2013).
[10] Asakura, et al., Processes 10 (2022) 872.

Detachment is produced: q_{target} is lower than 10 MWm^{-2}

Outer peak-q_{target} appears in "*partially attached*" region

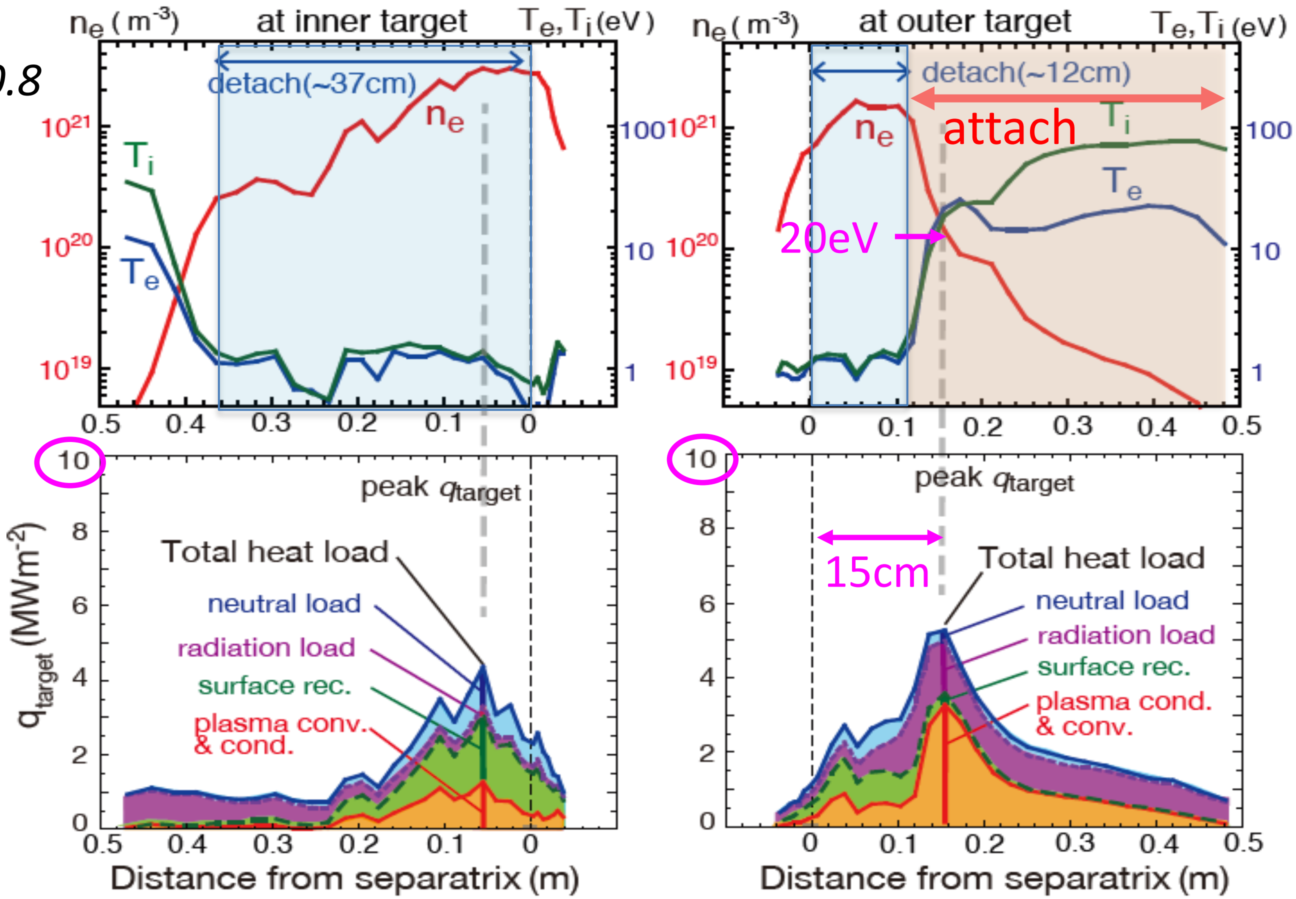
Inner target: peak q_{target}~4 MWm^{-2}, where ionization still occurs at $T_e^{div}=T_i^{div}$~1 eV.

⇒ Surface recombination is a dominant Volume-recombination is not significant.
Significant reduction in ion flux (seen in experiments) is *not* simulated.

Outer target: peak q_{target} ~5 MWm^{-2} is seen at "*attached*" region (r^{div} ~ 15cm).

⇒ Plasma heat load is dominant, and Radiation load is also large.

$P_{rad}^{div+sol}/P_{sep}$~0.8



[3]Asakura, et al. Nucl. Fusion 57 (2017) 126050

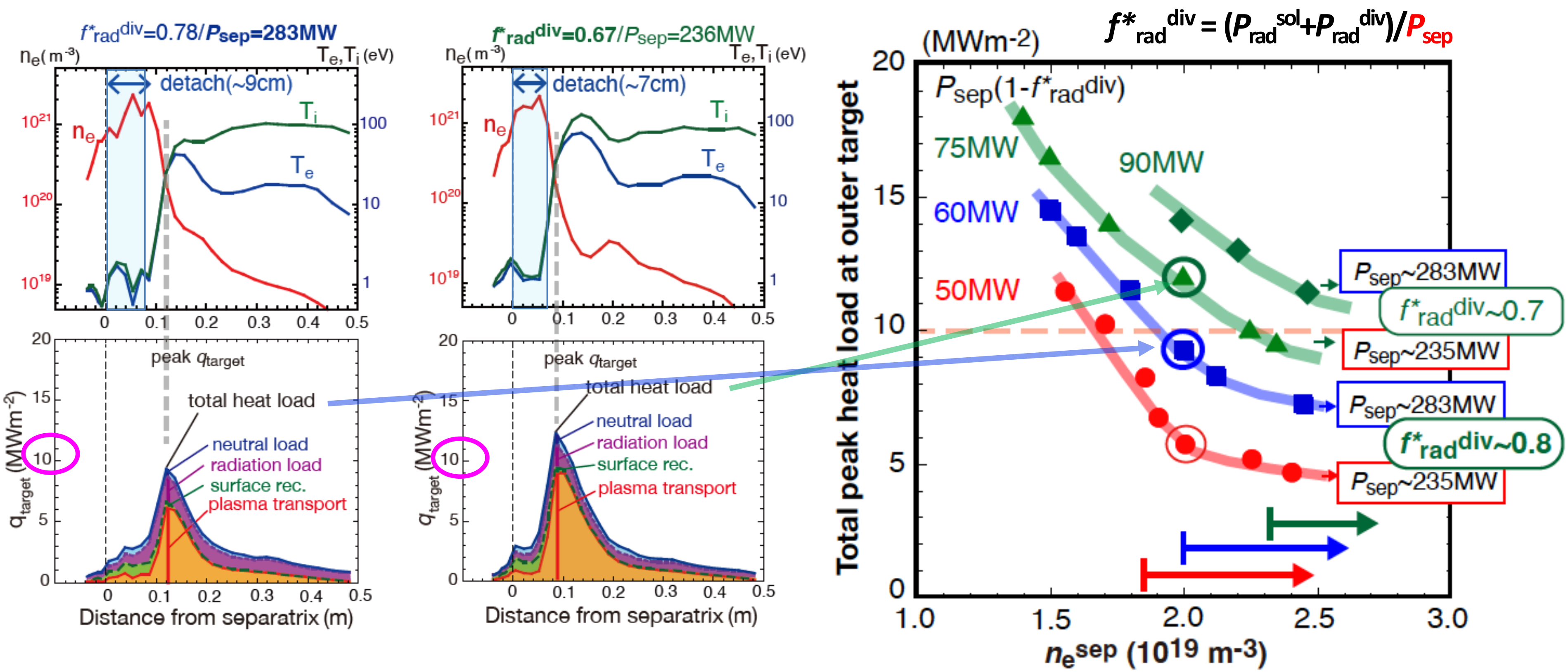
Divertor operation in low n_e^{sep} (= $n^{GW}/3$ ~ $n^{GW}/2$)

q_{target} is reduced (≤10MWm^{-2}) in *Both reference cases* ($f^*_{rad}{}^{div}$~0.8)

Severe cases were studied: high P_{sep}~283MW($f^*_{rad}{}^{div}$~0.8), low $f^*_{rad}{}^{div}$~0.7 (P_{sep}~235/283 MW)

⇒ Decreasing *detachment width* and increasing T_i and T_e *of the attached plasma*:

- q_{target} is increased, and margin of power handling (≤ 10 MWm^{-2}) is reduced.
- q_{target} is further increased ⇒ higher n_e^{sep} is required both for both *cases*.



[11] N. Asakura, et al., Nucl. Mater. Energy 26 (2021) 100864

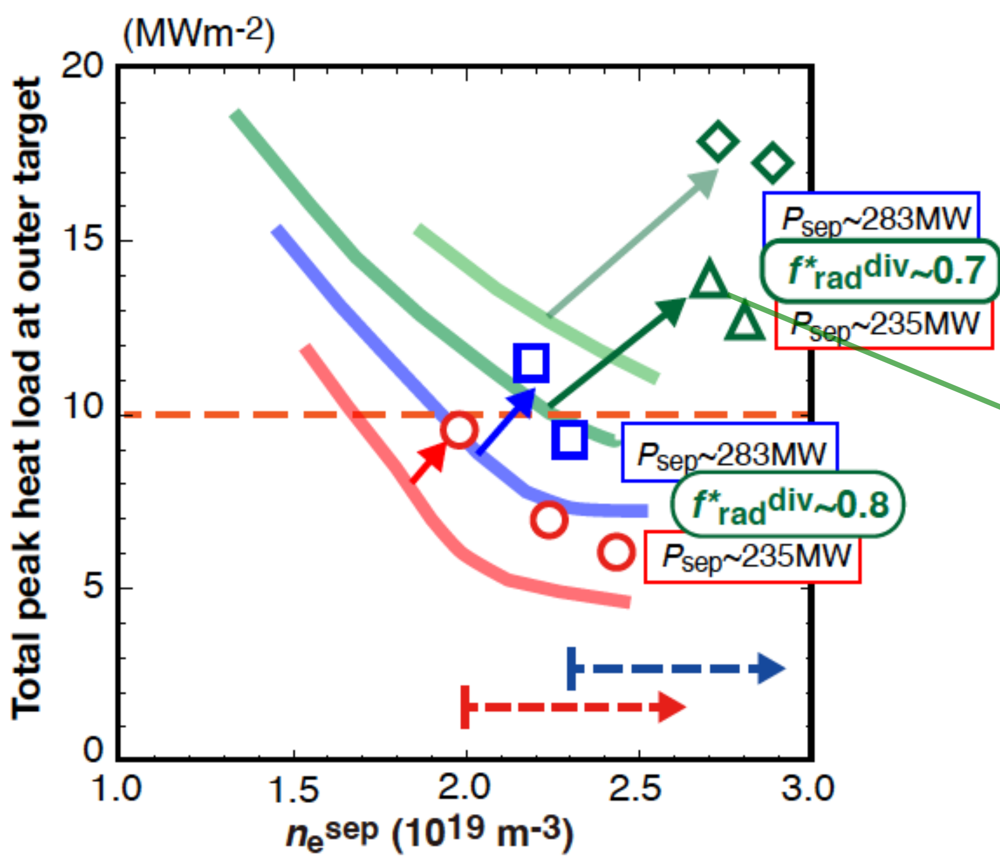
Divertor operation: smaller diffusion coefficients

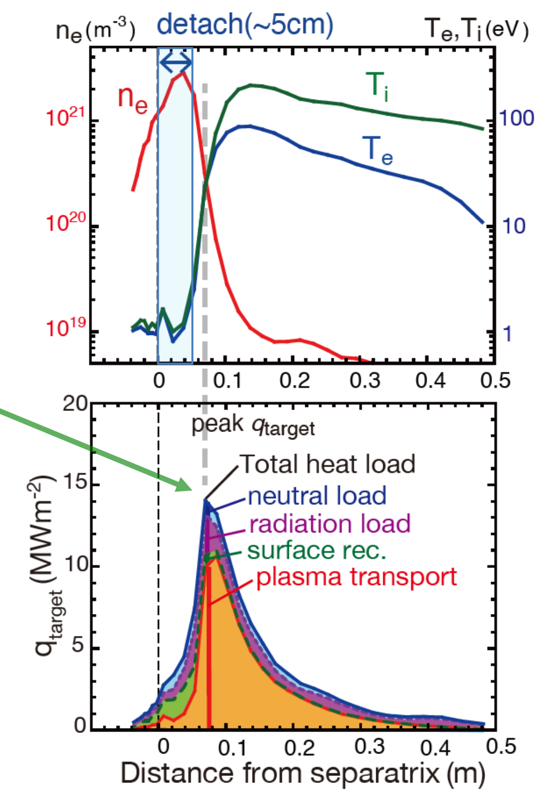
Influences of χ and D become large for *lower* radiation fraction

Peak-q_{target} for DEMO higher-κ and DEMO 2014 cases (f^{*div}_{rad} ~0.8) :

- Detachment region is reduced from 10 to 7 cm, and T_i^{div}, T_e^{div} *at attached region* increased
  ⇒ peak-q_{target} is increased, but acceptable for *higher-κ*, DEMO 2014(n_e^{sep} >2.3x10^{19} m^{-3}).

Low f_{rad}^{div} ~0.67 cases: divertor operation is difficult in the Low n_e^{sep} (2-3x10^{19} m^{-3}).



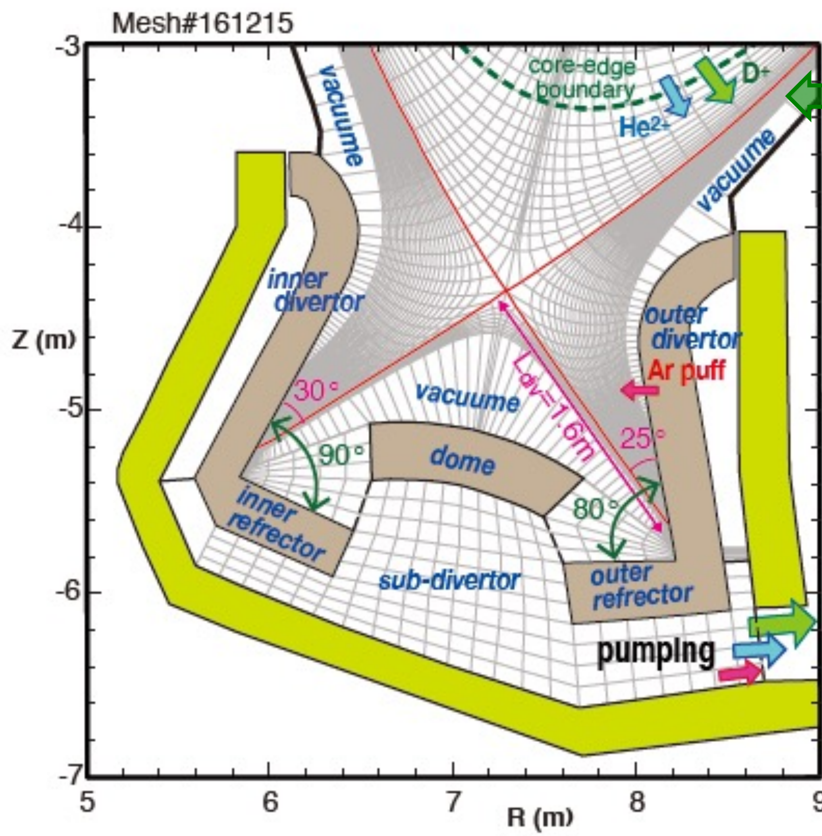


3. Particle and He exhaust study in DEMO divertor

He ion flux equivalent to P_{fusion}: 1.5GW is exhausted from *core-edge boundary*

Simulation parameters for *He exhaust study*:

- He flux (Γ_{out}^{He}=5.3x10^{20} s^{-1}) is exhausted, corresponding to P_{fusion} =1.5GW.
- D^+ flux (Γ_{out}^{D+} =1x10^{22} s^{-1}) outflux is assumed as pellet fueling level: $\Gamma_{out}^{He}/\Gamma_{out}^{D+}$**~5%.**
- Particle diffusion coefficient (D = 0.3 m^{2}s^{-1}) is same for D, He and Ar (same as ITER calc.).
- Simple diffusion process model (No neoclassical transport and pinch) is used inside separatrix.
- Elastic collision model of D^0-D^0, D^0-D_2, D_2-D_2, D^0-He, D_2-He was NOT applied in this series.
- Reflector angles were increased from 60° to (in)90°/(out)80° (for neutron protection)



Γ_{out}^{D+}:1x10^{22} Ds^{-1}, Γ_{out}^{He}=5.3x10^{20} Hes^{-1}

Gas puff from midplane

Γ_{puff} : 2.4-9.6x10^{22} Ds^{-1}

Same absorption probability is given for D, He, Ar.

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Neutral/molecular collision effects on pressure profile

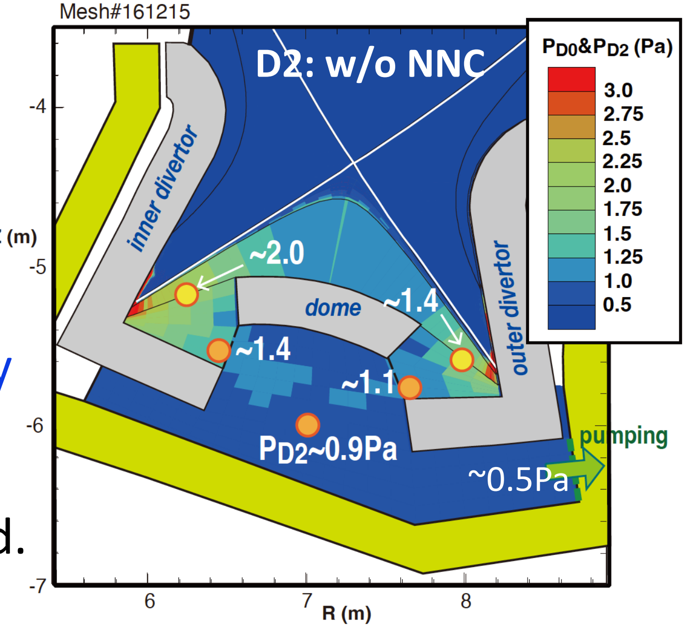
Neutral-neutral elastic collision (NNC) will increase P_{D2} in sub-divertor

Database of neutral-neutral elastic collision (NNC) was newly calculated [12, 13] in recent studies of detachment and exhaust:

- Collision rates and momentum exchange rates were evaluated from differential cross-sec. database for D_0-D_0, D_0-D_2 [14] and D_2-D_2 [15].
- NNC model is rather theoretical expression compared to those in EIRENE.

Effect of NNC model on D_2 gas pressure was significantly observed *in the sub-divertor* (2 times larger).

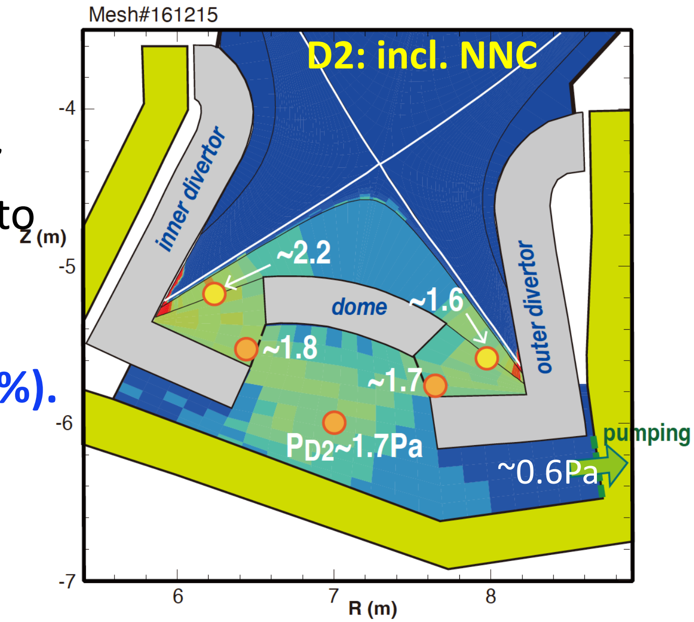
- P_{D2} at *the private* and *exhaust slots* were also increased.



But NNC model was NOT applied in this work.

***P_{D0}* distribution** in private and sub-divertor, and ***detachment*:**

- P_{D0} was rather decreased at *Inner private* (2.6→2.0Pa) due to D_0-D_0 /D_0-D_2 collisions near the strike-point.
- P_{D0} was reduced at lower than P_{D2} at both exhaust slots.
- **Reductions in target T_e and n_e were relatively small (10-15%).**



[12] S. Tokunaga, et al., PSI22, P.3.105, May 2016, Rome, Italy.
[13] K. Hoshino, et al., PET21, Session1-7, Sep. 2021, Remote
[14] P. S. Krstic et al., Atomic and Plasma-Material Data for Fusion 8 (1998) 1.
[15] A. V. Phelps, J. Phys. Chem. Ref. Data 19 (1990) 653.

Plasma detachment and D^0/D_2 pressure in divertor

Wider reflector angle: plasma detachment and neutral pressure were similar

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Gas puff 5.3×10^{22} Ds^{-1} and Ar seeding : 3.9×10^{20} Ars^{-1},

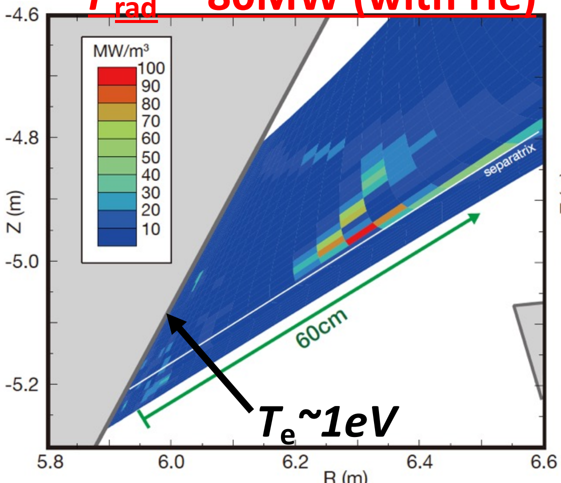
$f^*_{rad}{}^{div}$ = 0.78 (He radiation loss fraction is small: 0.04)

Inner target: Full detachment ($T_{e,i}$~1eV)

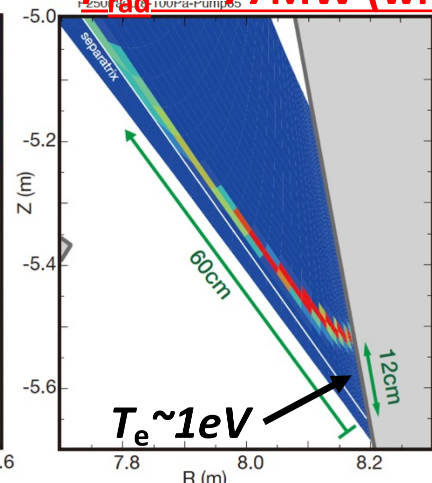
Outer target: Partial detachment ($T_{e,i}$~1eV in r^{div}<12 cm)

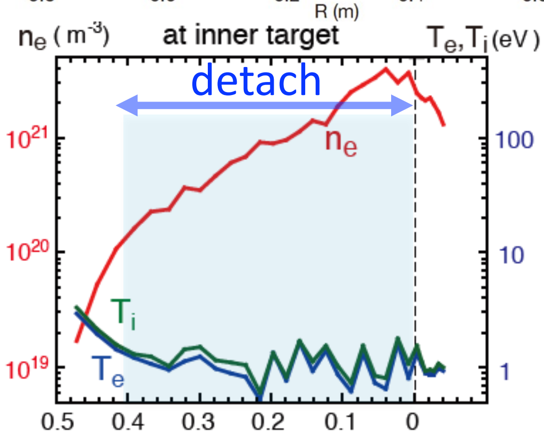
P_{D2} and P_{D0} are comparable at exhaust slots.

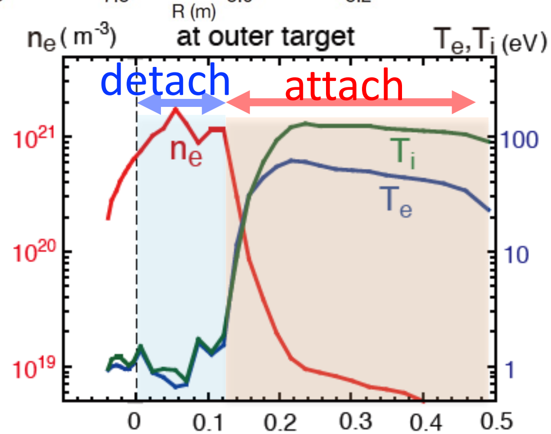
P_{rad}^{in}~80MW (with He)

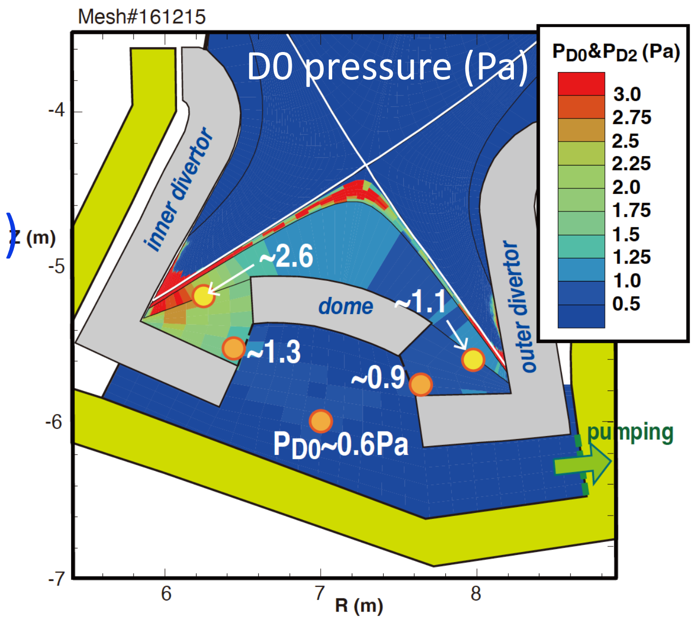


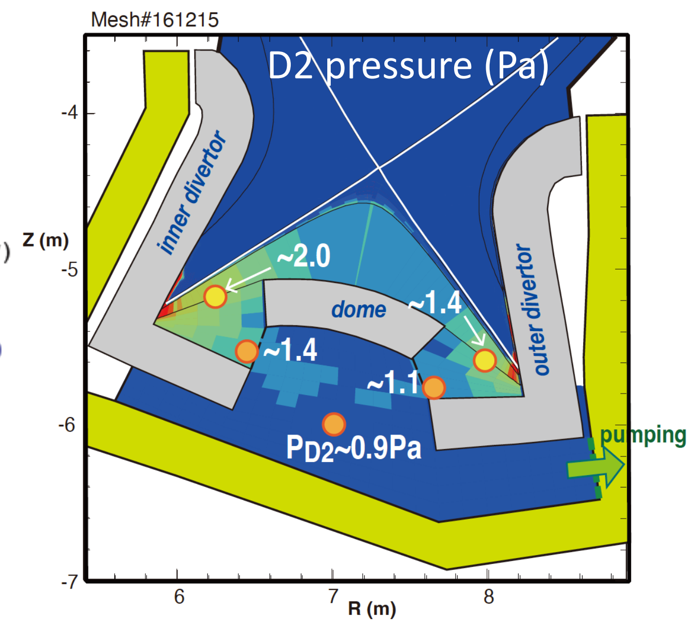
P_{rad}^{out}~77MW (with He)







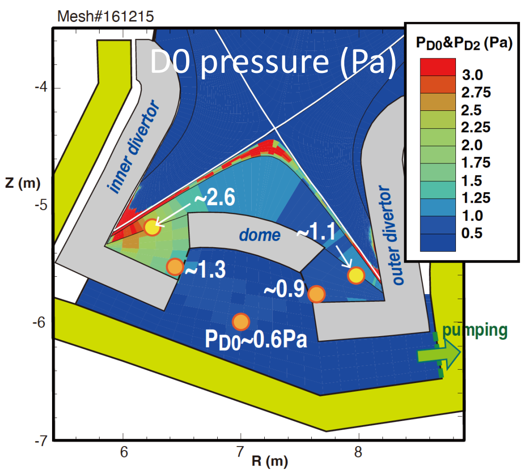


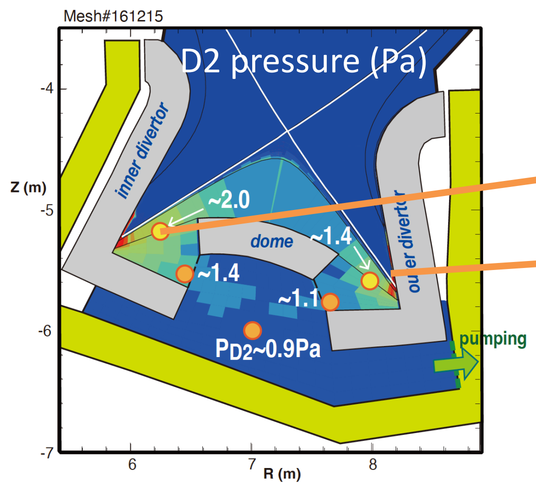


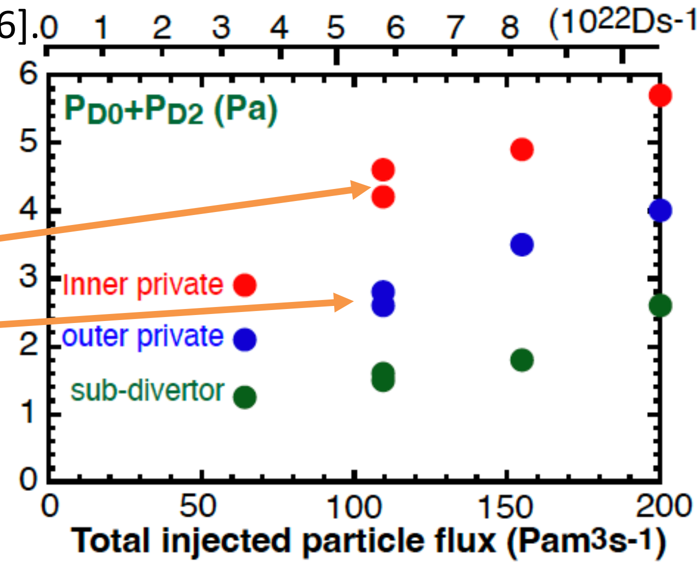
Inner and outer q_{target} vs divetor pressure

- Neutral pressure (P_{D2}, P_{D0}) at the private boundary was used, similarly to ITER.

But the pressure range was lower than ITER (~1/2)[16].

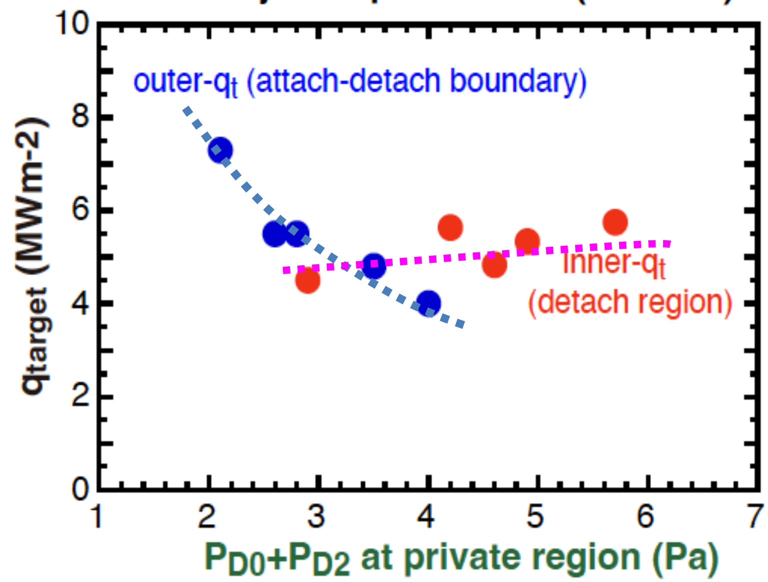






Peak heat load (q_{target}) :

- *Inner q_{target}* is maintained: it is seen in detached region ($T_{e,i}^{div}$ = 1-2eV), and high Γ_i^{div} and n_e^{div} are maintained.
- *Outer q_{target}* is decreased with $P_{D0,D2}$: it is produced at attached region, where *local* $T_{e,i}^{div}$ decreases with $P_{D0,D2}$.



[16] R. Pitts, et al., Nucl. Mater. Energy 20 (2019) 100696.

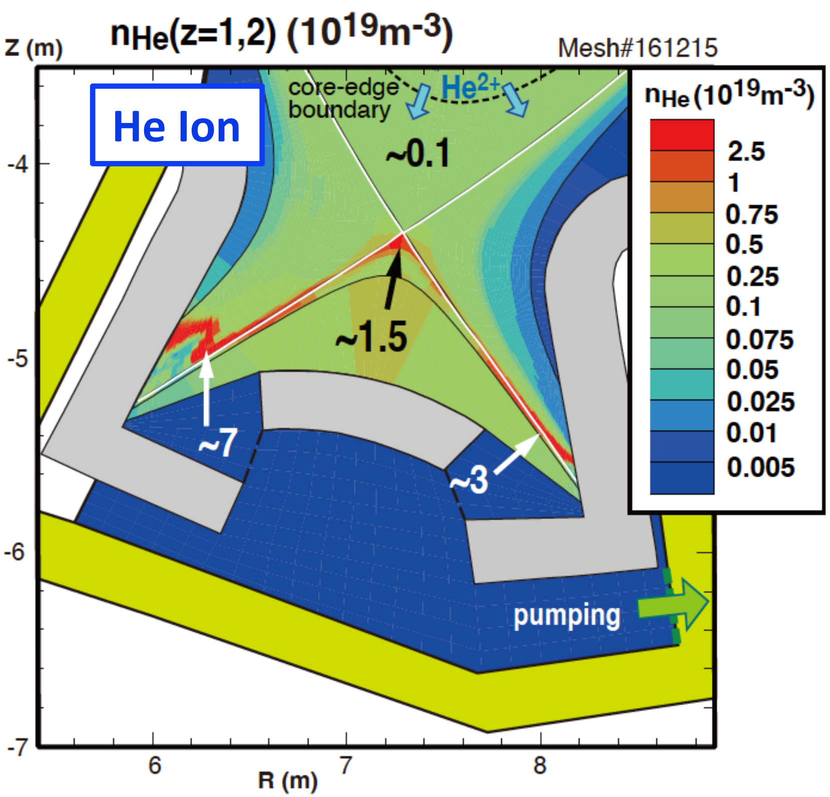
He ion and atom densities in plasma edge and divertor

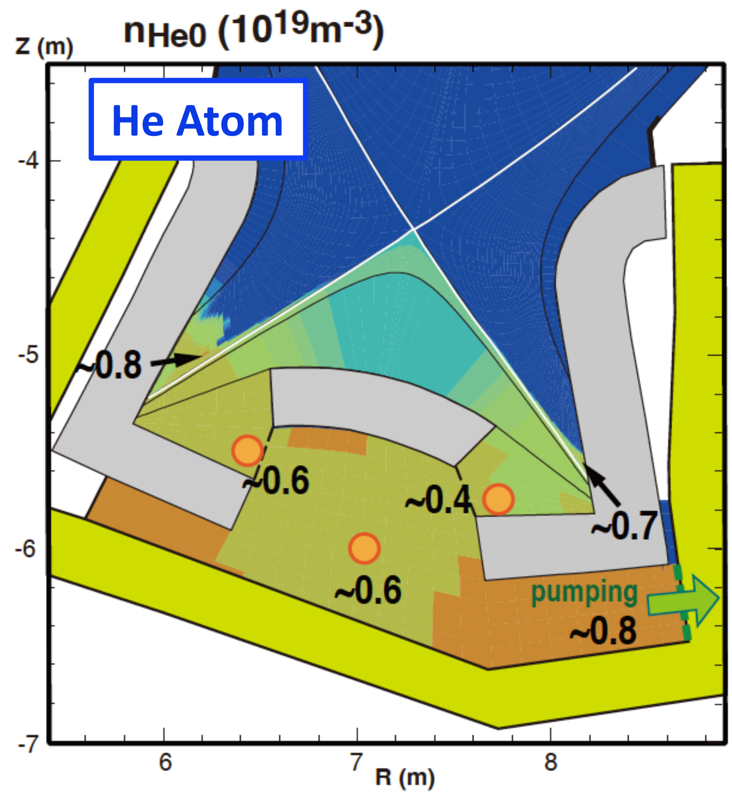
He ion density (n_{HeZ}) is significantly increased near the detachment front
（between Ar radiation peak and D ionization front）due to recycling in the divertor:

- n_{HeZ} is increased also at the private region *near X-point*（similar to D^+ density）.
- n_{HeZ}~1×10^{18} m^{-3} *inside the separatrix* (r^{mid}/a=0.96-0.98).

He atom density (n_{He0}) in the divertor:

- n_{He0} is increased at the downstream of ionization front.
- n_{He0} is rather uniform in sub-divertor, and increased at exhaust route (E_{He} is reduced).





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He concentration in detached divertor

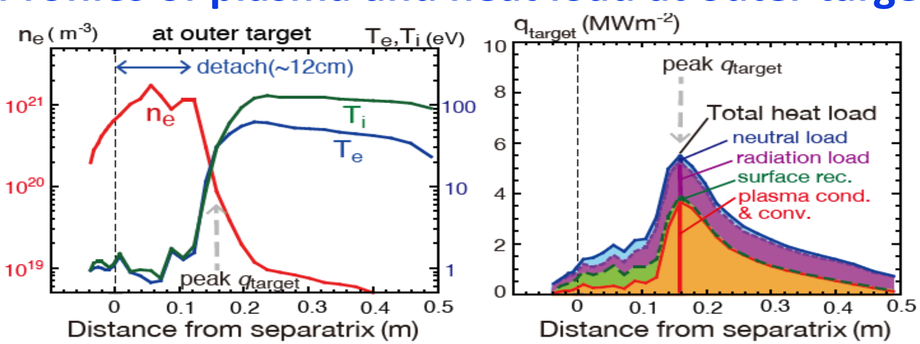
C_{He}^{edge} = 4-7% similar to exhausting Γ_{He}/Γ_D: Accumulation of He is NOT seen.

With increasing gas puff rate, *detachment width* increases and *peak* q_{target} is reduced.

He concentrations at SOL and plasma edge ($C_{He} = n_{He}/n_i$) for χ **=1/*D* = 0.3 m^{2}s^{-1} case:**

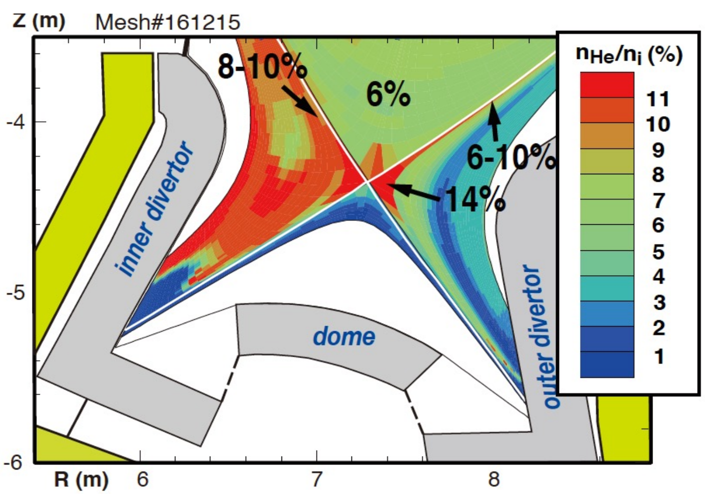
- In-out asymmetry of C_{He} in SOL/divertor is 2-3 times, but decreasing near separatrix.
- C_{He} = 4-7% at plasma edge (smaller than SOL) ⇒ Accumulation of He is NOT seen.

Profiles of plasma and heat load at outer target:

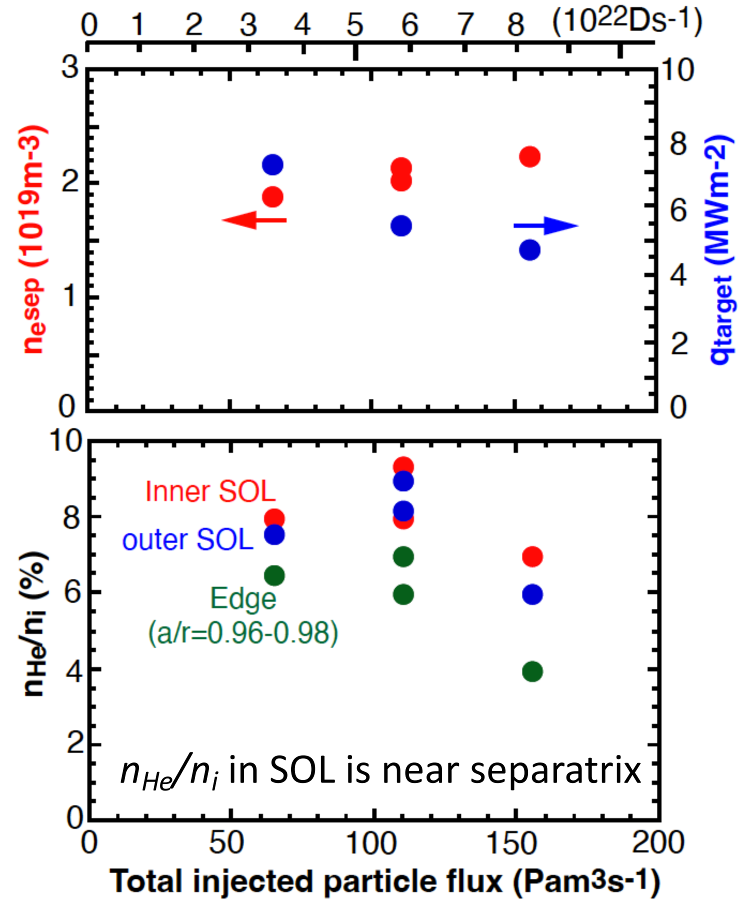


He concentration (C_{He}=n_{He}/n_i) in divertor

$\chi_{i,e}$ =1m^{2}s^{-1}
$D_{i,He}$ = 0.3m^{2}s^{-1}



midplane density and **peak heat load**



Effect of diffusion coefficients on He exhaust

χ and D were reduced to half values: He concentration is acceptable.

χ and D were reduced to half values (0.3/0.15 m^2s^{-1}) :

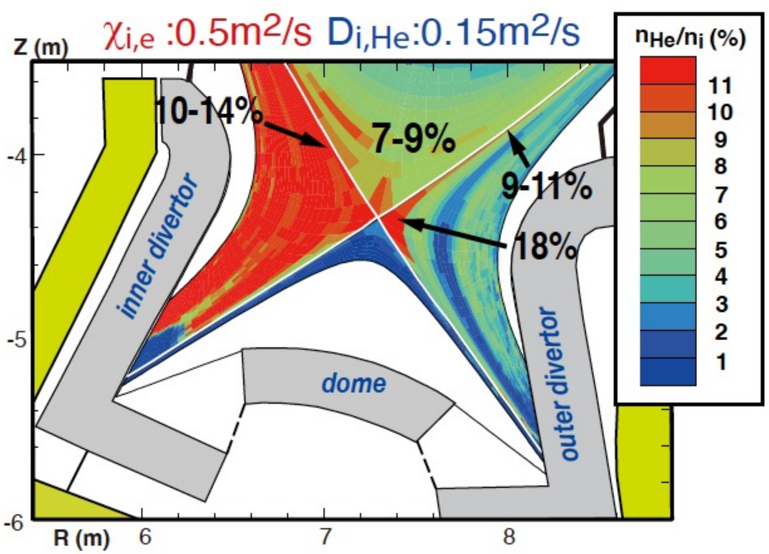
- C_{He} (=n_{He}/n_i) increases to 10-14% (inner SOL), 9-11% (outer SOL) and near X-point (18%).
- C_{He} at plasma edge is increased from ~6% to 7-9%.

n_e^{sep} (midplane) is 25% larger than n_i^{sep} due to Ar and He ions (similar contributions).

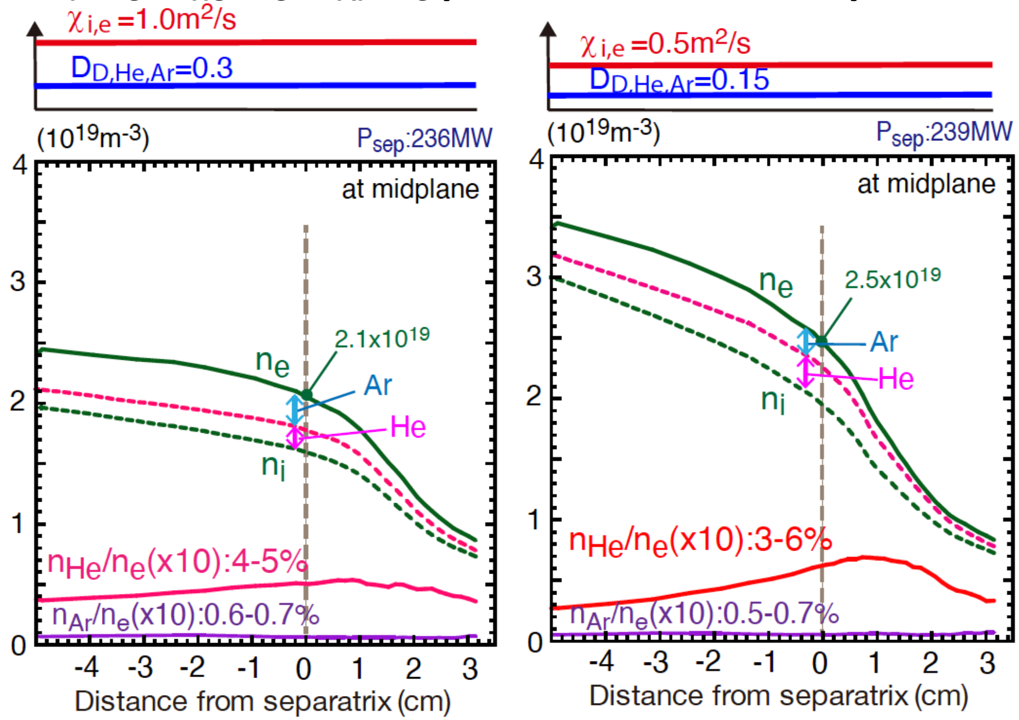
- Effect of reducing χ and D: n_{He}/n_e profile changes inside the midplane separatrix: reduction from 5% (r^{mid}/a=1) to 4% (0.98) is enhanced from 6% to 3%.

Uniform n_{He}/n_e =7% is assumed for JA DEMO design by system code: acceptable level

He concentration: C_{He}= n_{He}/n_i



n_i, n_e, n_{He}/n_e, n_{Ar}/n_e profiles at outer midplane



5. Summary: Simulation of JA DEMO divertor performance

Heat load and plasma detachment in a long-leg divertor (L_{leg}=1.6m) were evaluated for JA-DEMO 2014(P_{sep}= 283MW) and higher-κ (P_{sep}= 235 MW) in low SOL n_e^{sep}= 2-3x10^{19}m^{-3}.

Divertor operation (≤10 MWm^{-2}) was determined with reducing $f^*_{rad}{}^{div}$ or/and χ & D;

- Peak-q_{target} in outer divertor appeared *at detach-attach boundary*, and it was increased with decreasing partial detachment width and increasing the local-T_e^{div} and T_i^{div}.
- *Two references* ($f^*_{rad}{}^{div}$ ~0.8) was acceptable; higher-κ case allows larger operation margin.
- Severe cases of reducing $f^*_{rad}{}^{div}$ to ~0.7 *or* χ and D to half values; higher n_e^{sep} was required. Particularly, impact of reducing both χ and $f^*_{rad}{}^{div}$ was serious.

Simulation for particle and He exhaust has been developed;

- Neutral-neutral elastic collision (NNC) will increase particularly P_{D2} in the sub-divertor.
- Accumulation of He ion was NOT seen in the plasma edge: $(n_{He}/n_e)^{edge}$~4-5% while increasing the partial detachment width.
- For reduced χ and D case, $(n_{He}/n_e)^{edge}$ is acceptable, while C_{He} was increased in SOL.

Some future activities and developments:

- Relationship between q_{peak} (and components) and P_{D2}/P_{D0} is investigated.
- **Benchmark of SONIC and SOLPS-ITER codes** both for EU- and JA-DEMOs.
- **Integration of transport codes, SONIC and TOPICS (1D, main plasma)**, is in progress.
- **Renewing SOLDOR to incorporate drifts** is considered; now debugging in slab-model.