原型炉ダイバータにおける熱制御課題

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Introduction

Role of divertor

Heat exhaust, He ash exhaust, Impurity control

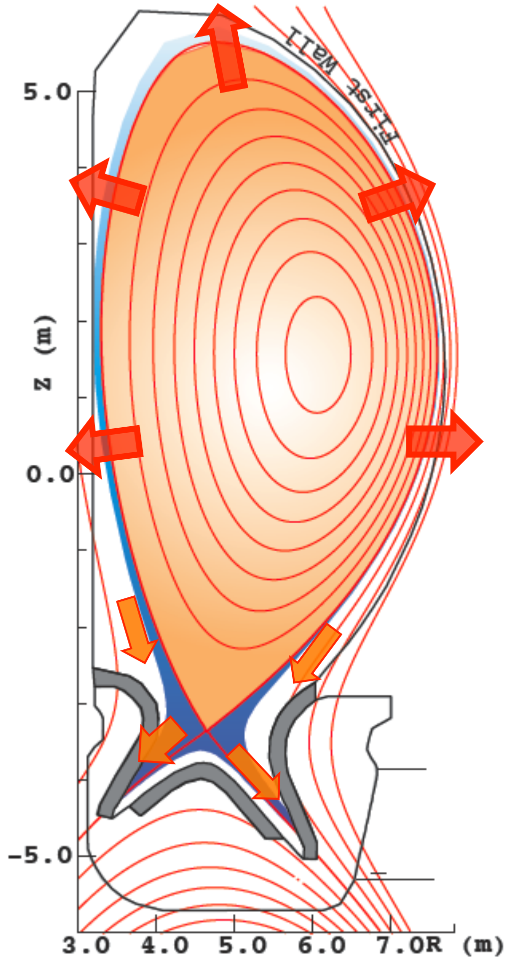
Basic divertor concept for JP DEMO

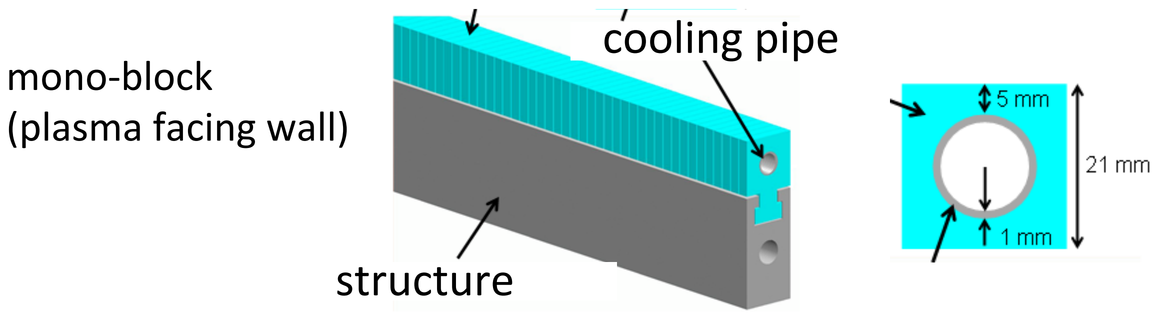
Divertor plasma detachment is a key for

- reduction of the target heat load
- suppression of the target erosion

Design concept for the ITER divertor is extended to DEMO divertor.

- W mono-block divertor target
- Enhancement of the divertor recycling
  V-shaped geometry, long-leg, target inclination
- impurity seeding such as Ar (Ne, N2, Kr, Xe, etc)





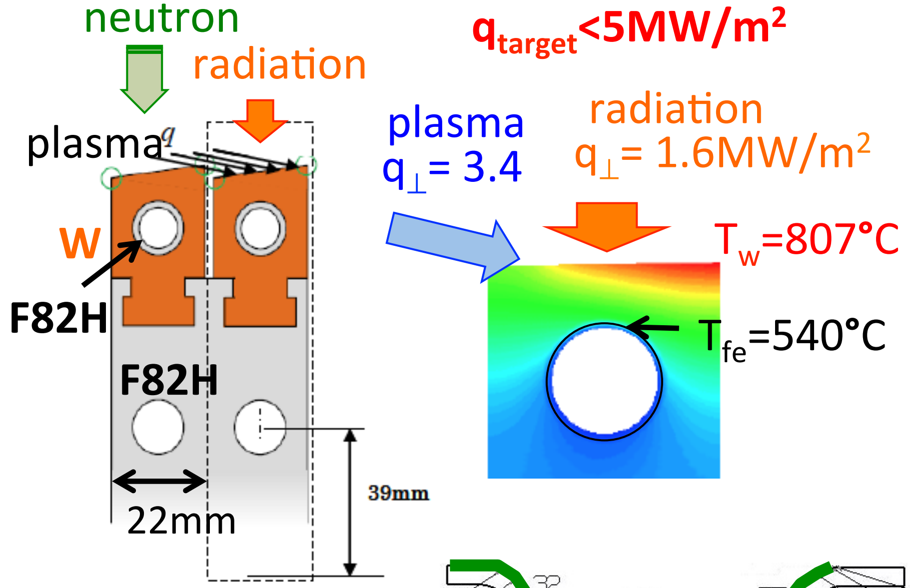
Heat removal capability of divertor target

Strong neutron irradiation environment

→ **W** for armor
RAFM for structure & cooling pipe

Max. q_{div} ~ 5 MWm^{-2} was restricted by joint T_{Fe} = 550 °C rather than T_W.

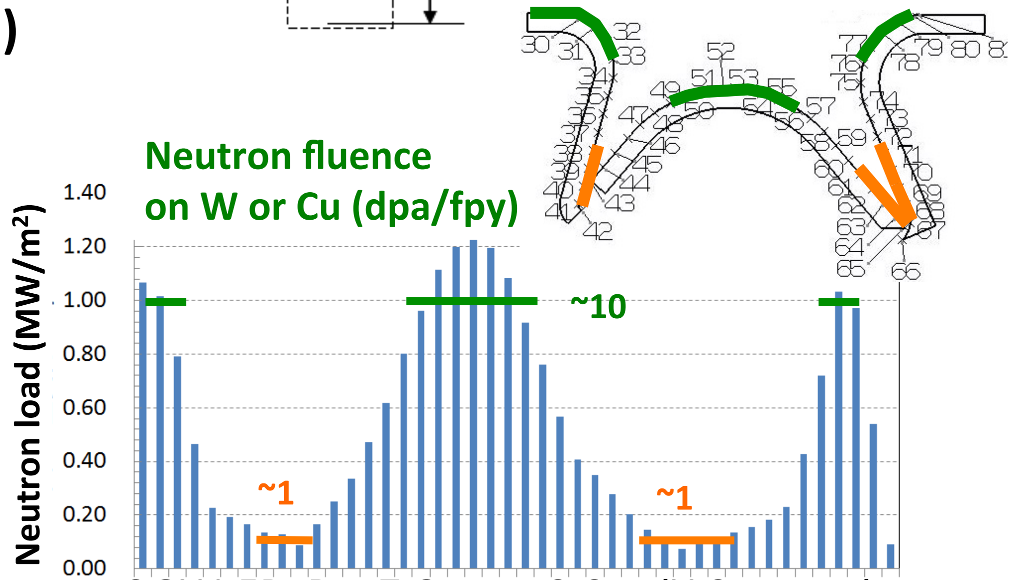
Heat loading



Possibility for Cu-alloy cooling pipe under low n-irradiation environment (< 1 dpa)

divertor geometry
lower fusion power
larger machine size, etc.

Max. q_{div} increases to 10MW/m²



2GW-FP, R = 7.8m, a=2.2m (Y.Someya)

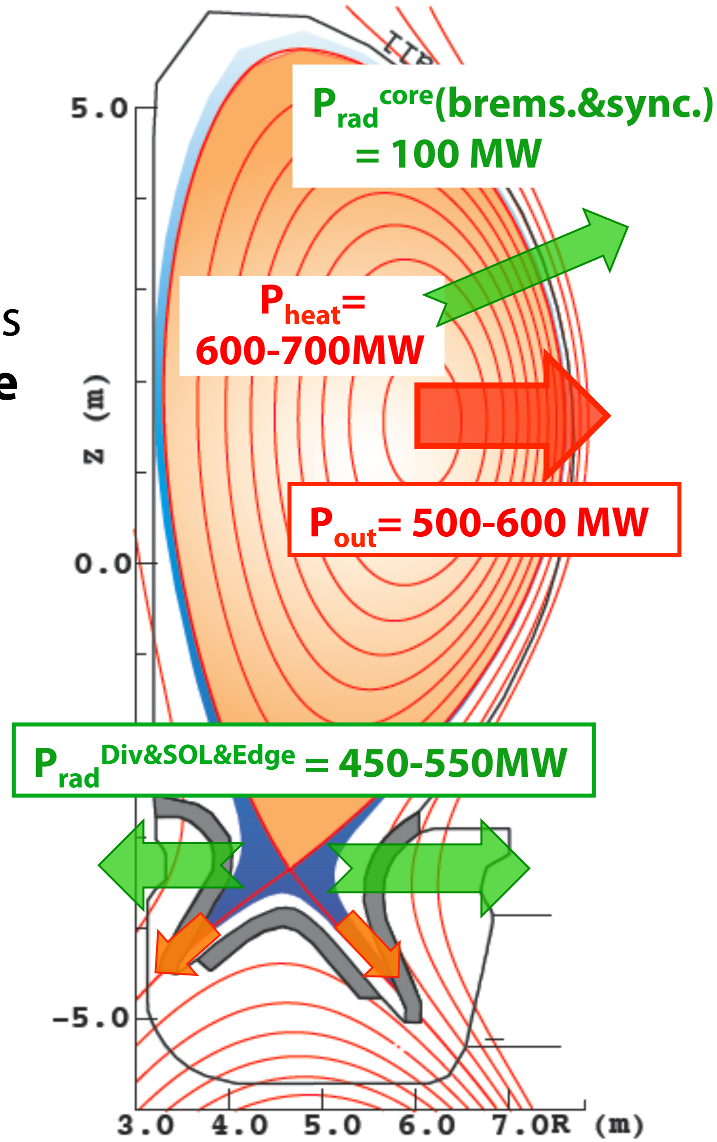
Power handling scenario in DEMO divertor

E.g.)

P_{fus}=3GW with **ITER size plasma** such as SlimCS

- ✓ **Power exhausting to SOL is 500-600 MW.** which is 5-6 times larger than ITER.
- ✓ **Power handling capability** of divertor target is **5-10 MW/m²**, which is **less** than or **comparable** to ITER.
- ✓ **> 500MW** must be handled in Div./SOL/Edge. ➔ Primary technic is **Impurity radiation**

Power handle	SlimCS	ITER
P_{heat} (α + external)	650 MW	150 MW
$P_{out} = P_{heat} - P_{rad}^{core}$	**550 MW**	100 MW
P_{div} (= $P_{out} - P_{rad}^{D/S/E}$)	**< 50MW** (<10MW/m²)	~50MW (~10MW/m²)
⇒ $P_{rad}^{Divertor/SOL/Edge}$	**> 500MW**	~50MW



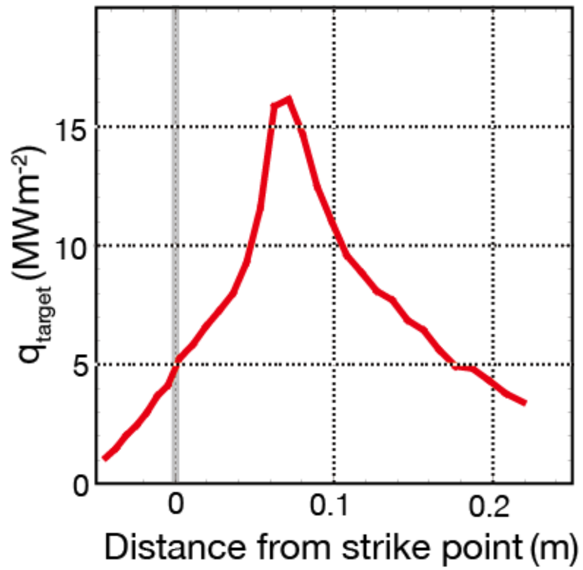
Divertor power load under large impurity radiation

SlimCS divertor simulation by SONIC
with the large Ar impurity radiation power
(P_{rad}/P_{out} = 460/500 MW = 92%)

Although 92% of the exhausting power is radiated,
the divertor power load is still higher than 10MW/m^2.

There are large gap from the present experiments on development of power handling scenario in a viewpoint of both **the huge exhausted power** and **the large impurity radiation fraction**.

power load on outer target

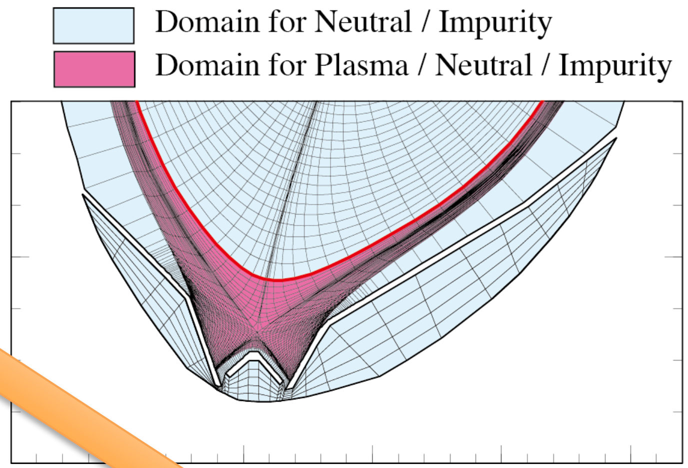


Development of the power handing scenario is challenging issue
and
predictive simulation study has an important role.

H. Kawashima, Nucl. Fusion 2009) N. Asakura, NF2013

A suite of integrated divertor codes, SONIC

H. Kawashima PFR2006, K.Shimizu NF2009



SONIC

SOLDOR

fluid model
- ion particle conservation
- parallel ion momentum conservation
- ion and electron energy conservation

Plasma (fuel ion)

NEUT2D

Monte-Carlo particle model
- Boltzmann eq.
- A&M, Geometry effect, pump…

Neutrals(fuel)

IMPMC

Monte-Carlo particle model
- Guiding center approximation
- Kinetic effects, PWI …

Impurity(He, Ar, C, W …)

- Impurity transport is treated by MC model IMPMC.

- SONIC is optimized on the massive parallel computer

→ Steady-state solution can be obtained with **6-30 hours** on HELIOS

→ Advantage in **various parameter survey**

Numerical condition for DEMO divertor simulation

To evaluate the divertor power load and
to develop the divertor power handling scenario,
SONIC(V2) simulation has been carried out.

Input parameters

At core boundary(r/a~0.95):

$Q_i=Q_e=250MW$, (= fusion power of 3GW)

$n_{ion}=7.0x10^{19}\ m^{-3}$

anomalous transport coefficient:

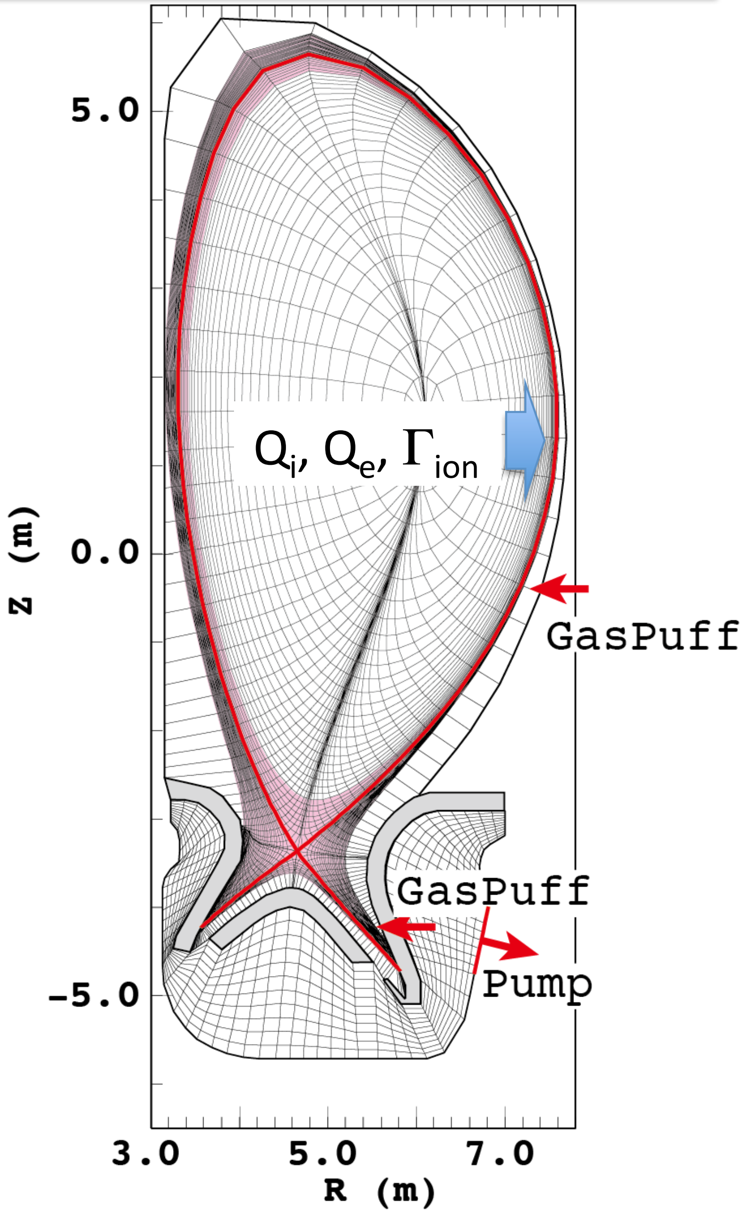
$D=0.3m^2/s$, $\chi=1.0m^2/s$ (spatially const.)

D gas puff: $\Gamma_{puff}=1x10^{23}\ s^{-1}$ (div. + sol)

pumping speed: $S_{pump}=200\ m^3/s$

wall recycling 100%

Ar Impurity gas puff (div.) adjusted by feedback
to achieve $P_{rad}/P_{out}=0.92$



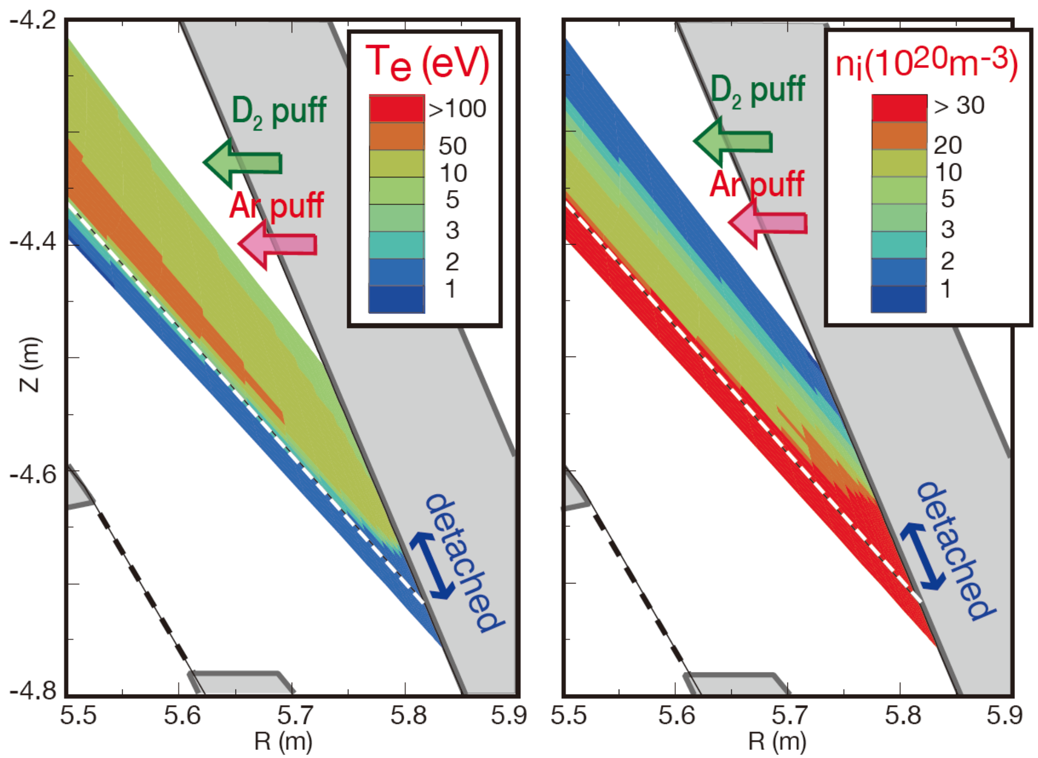
numerical grid for SlimCS

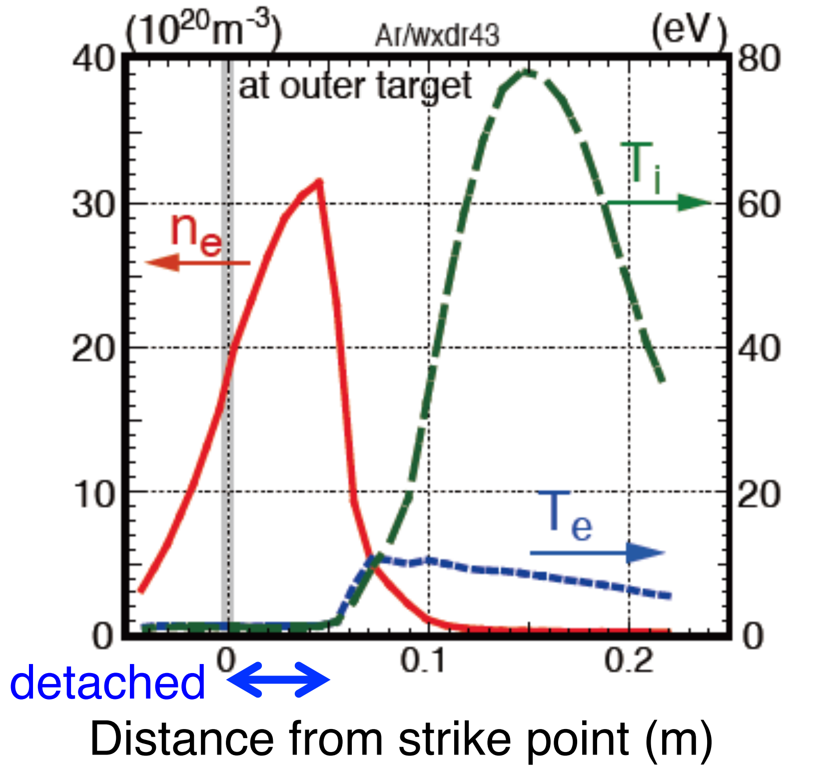
Detachment in high radiative divertor

P_{rad}^{tot}/P_{out} is increased to ~92% (P_{rad}^{tot} = 460MW) by Ar puff rate of 12 Pa m^3 s^{-1},

Partial detachment (T_e < 1-2 eV) is seen ***near the outer strike-point*** **(< 5 cm), and**
Plasma is attached (T_e = 10 eV, T_i = 80 eV) ***at outer flux surfaces***
due to low density and low collisionality.

Spatial profiles near outer divertor target





Target heat load profile at the outer target

Control of the detachment and the radiation distribution is important issue.

Plasma heat load is reduced to < 8 MWm^{-2} due to the partial detachment.

Surface recombination of low-temperature ions contributes near the strike-point.

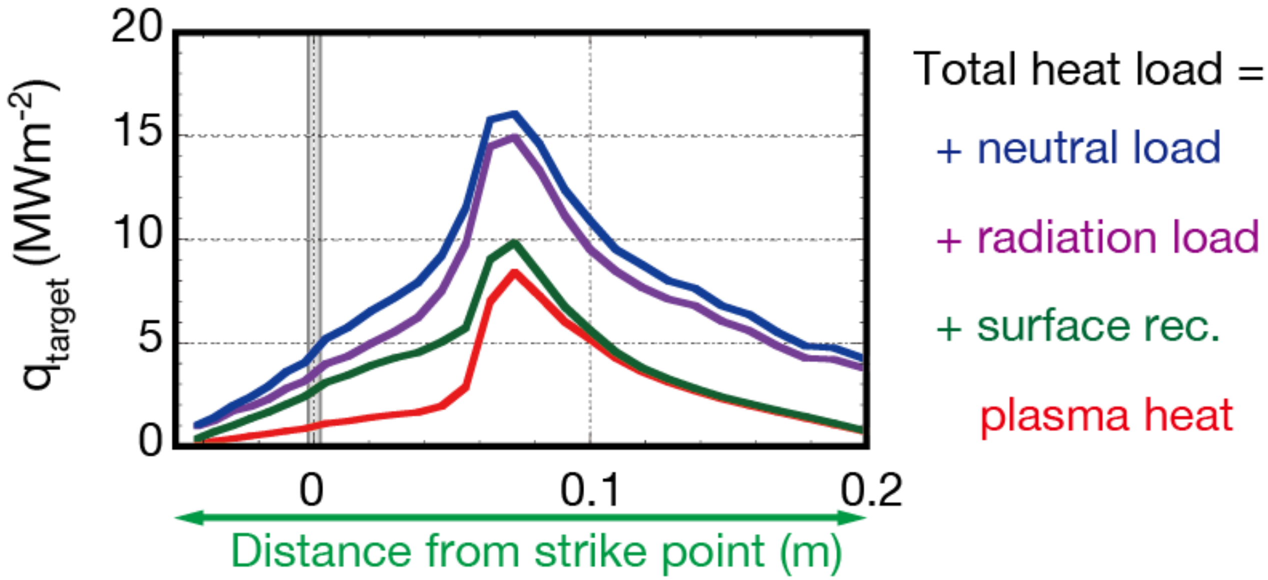
Radiation power load is large (3-5 MWm^{-2}) *over a wide area in the divertor*

⇒ peak of total power load is ~16 MWm^{-2} due to radiation source near above target.

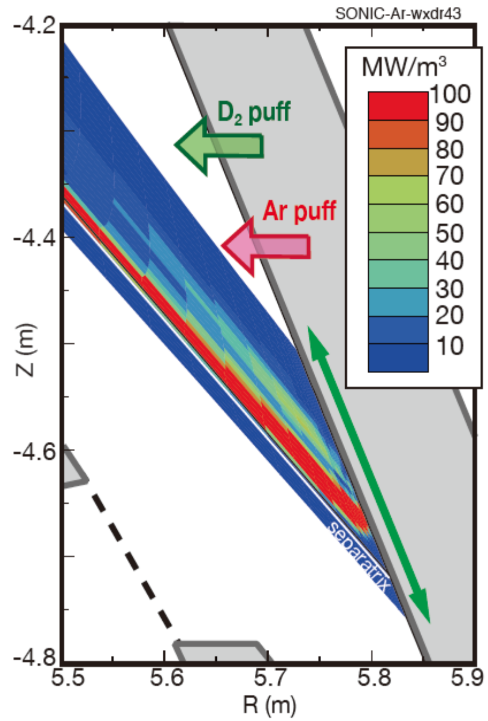
Total power load on the target:

$$q_{target} = \gamma \cdot n_d \cdot C_{sd} \cdot T_d + n_d \cdot C_{sd} \cdot E_{ion} + f_1(P_{rad}) + f_2\,(1/2 m v_0^2 n_0 v_0)$$

- $\gamma \cdot n_d \cdot C_{sd} \cdot T_d$: Plasma transport (conduction/convection of electron & ion)
- $n_d \cdot C_{sd} \cdot E_{ion}$: Surface-recombination
- $f_1(P_{rad})$: radiation power load
- $f_2\,(1/2 m v_0^2 n_0 v_0)$: neutral load



Radiation distribution



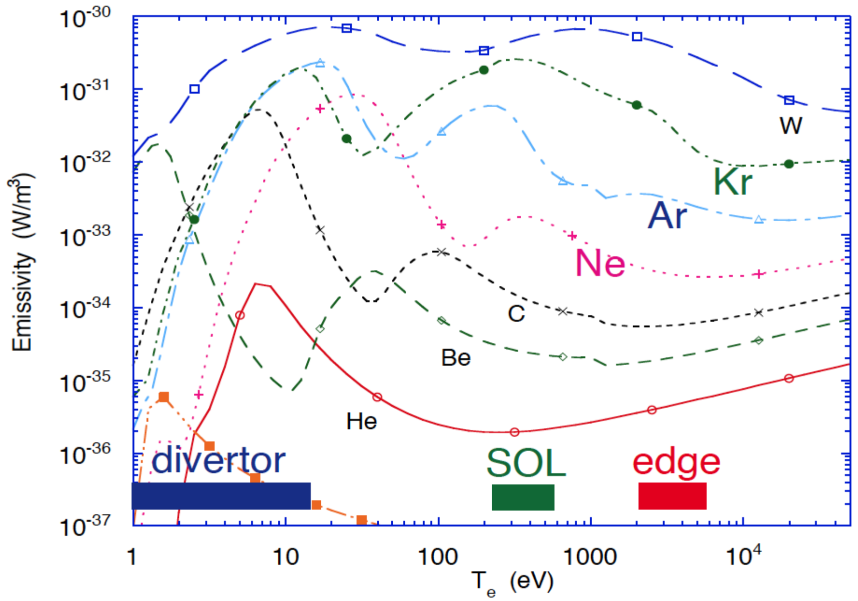
Control of the impurity radiation profile

To reduce the total divertor power load, control of the radiation profile is studied.

1) **Seeded impurity species:** Ne, Ar, Kr, …
   Noble impurities radiate photon efficiently, enhancing at high T_e with Z.

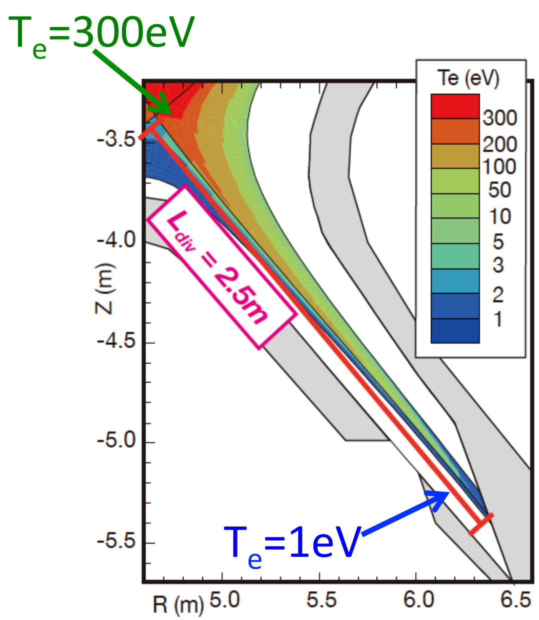
2) **Divertor geometry:** leg length, target inclination, flux expansion …..
   Long leg divertor decreases $T_{div} \propto q_{//}^{10/7}/n_u^2 L_{//}^{4/7}$ (from 2-point model),
   and **enhances recycling and produces detachment efficiently.**

Radiation loss rate coefficients



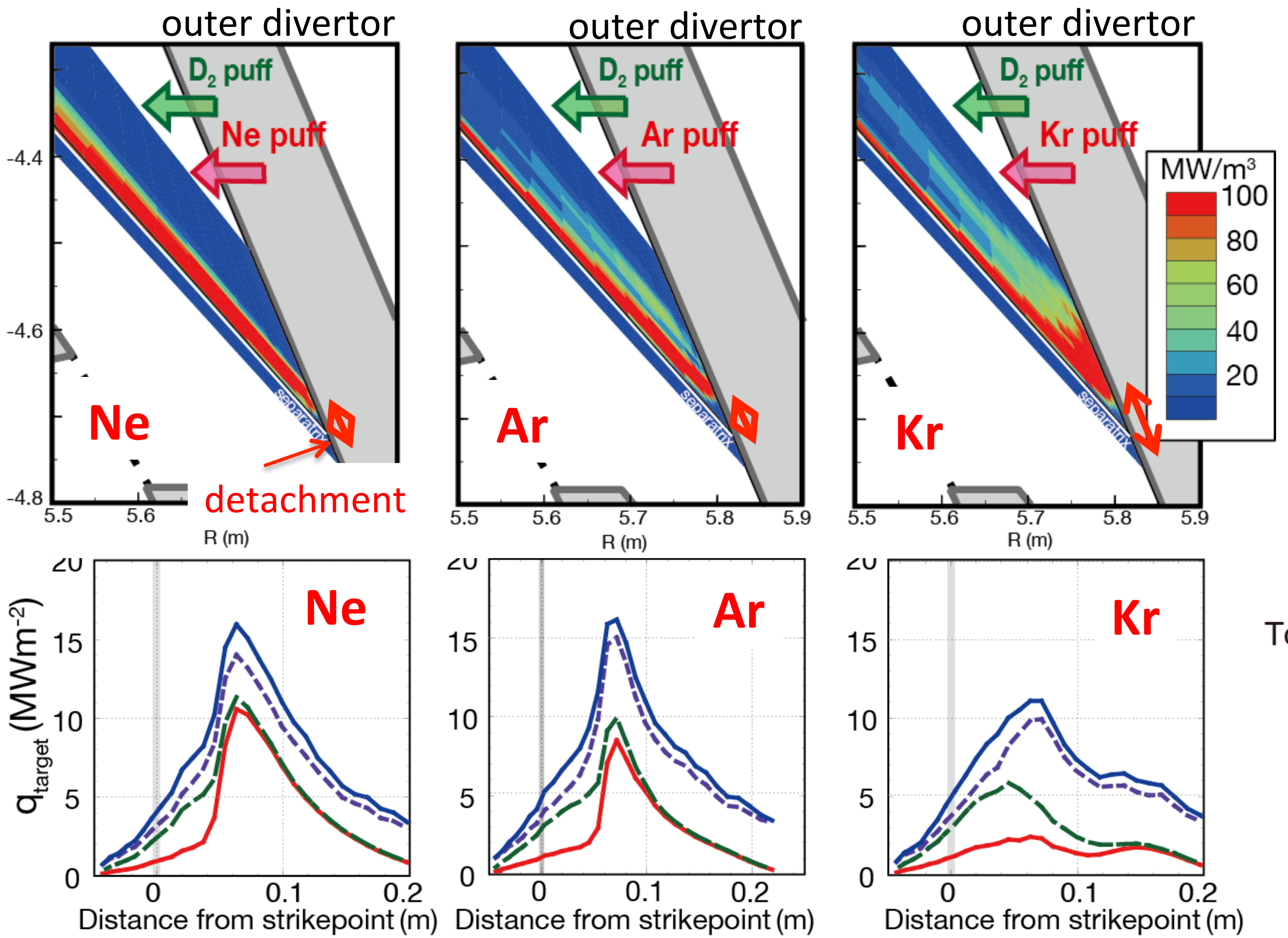
ITER physics Basis, Chap. 4, NF, 39 (1999) 2391

T_e distribution in *Long leg divertor*



Effect of seeded impurity species

Radiation region and detachment extend and the peak power load decreases for higher Z. **→ Higher Z impurity is preferable for the divertor power handling.**



All cases:
P_{rad}^{tot} = 460MW
(P_{rad}^{tot}/P_{out}~92%)

puff	10^{21} atm/s
Ne	3.8
Ar	1.5
Kr	0.93

Total heat load =
plasma heat load
+ surface rec.
+ radiation load
+ neutral load

N.Asakura NF2013

Effect of seeded impurity species

Shielding effect in the divertor for Ne, Ar, Kr is comparable.

$[(n_Z/n_i)^{div}/(n_Z/n_i)^{SOL}] = 1.5\text{-}2.$

→ **Concentration** in SOL **is determined by** that in **divertor** ~ puff rate.

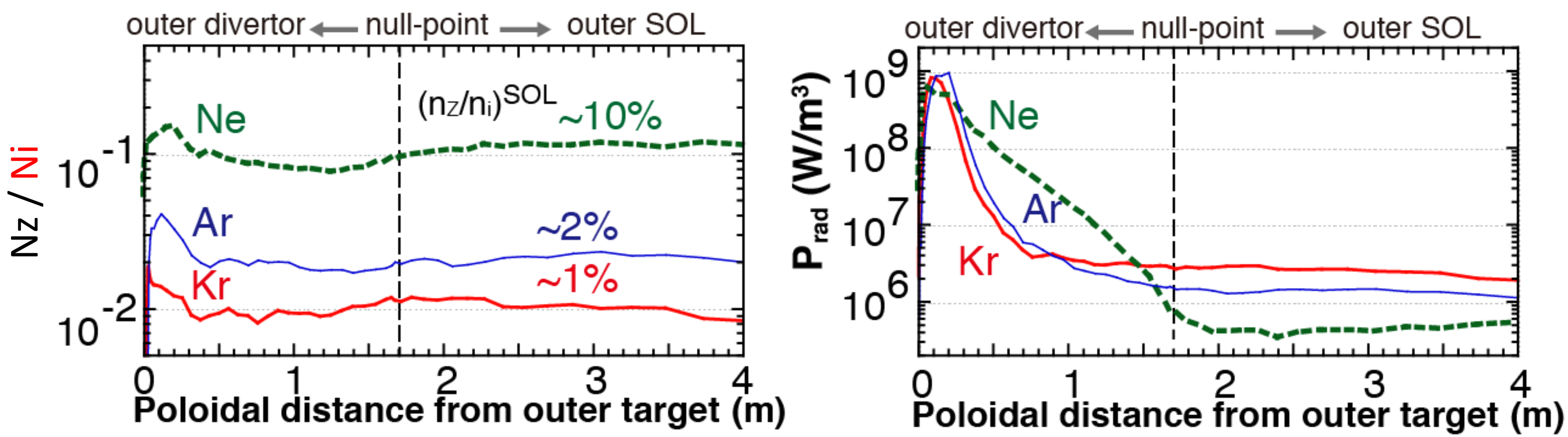
To achieve the large impurity radiation fraction of 92%,

the **impurity concentration in SOL becomes large**.

Large radiation power in the SOL and edge region for higher-Z

(P_{sol}, P_{edge}) (MW) = (48, 39) for Ne → (98, 53) for Ar → (108, 121) for Kr

Consistency with the core performance is open issue.



Impact of the divertor geometry: Long-leg divertor

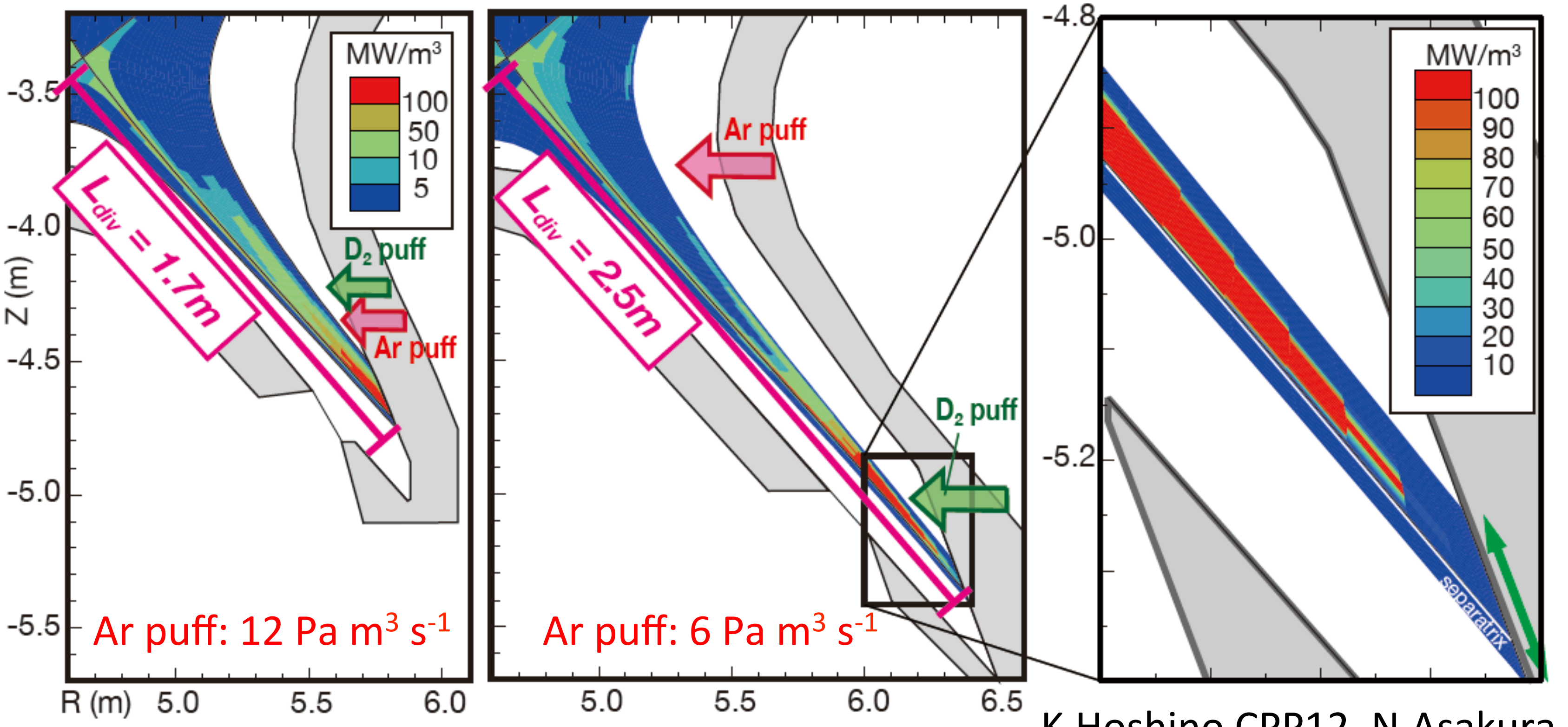
Divertor leg (L_{div}) is extended from 1.7 to 2.5m, while flux expansion is reduced:

"Long leg divertor" can decrease T_{div} and enhance particle & impurity recycling and produces detachment efficiently.

- **Strong radiation region moves upstream, and still stays in the V-shaped corner ⇒ producing *full detachment***

Radiation profile in Ref. slimCS divertor

Radiation profile in Long-leg divertor



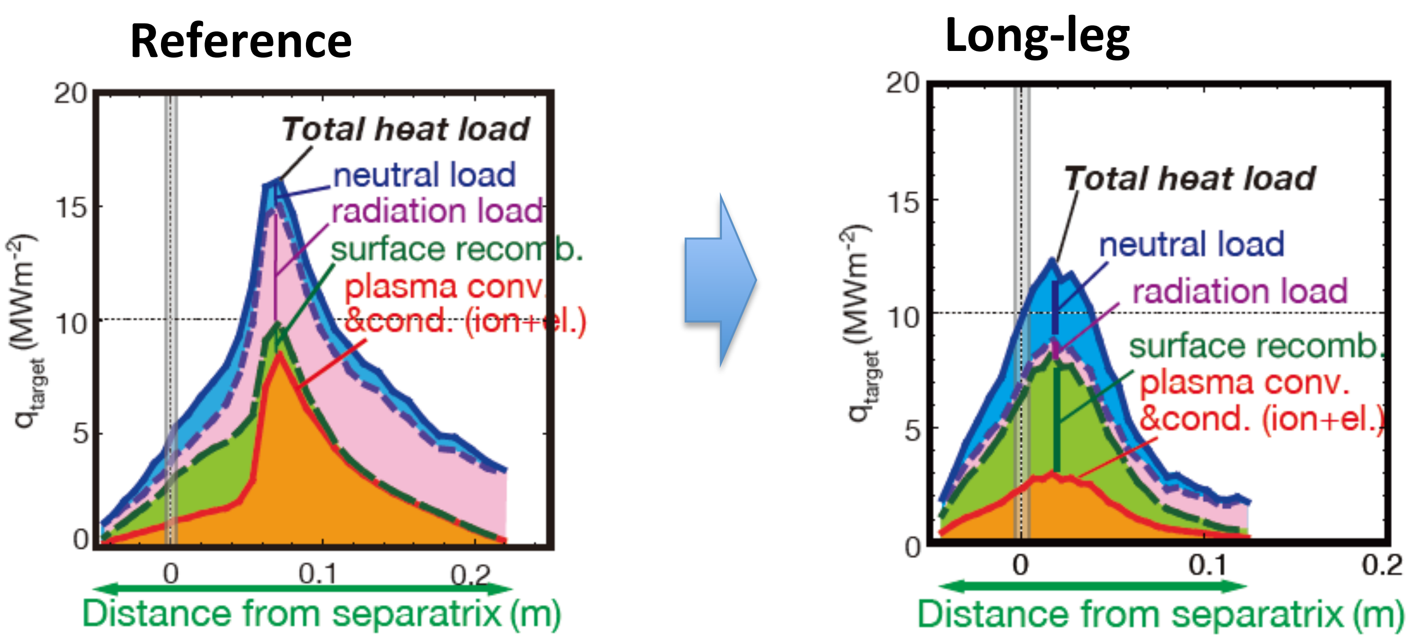
K.Hoshino CPP12, N.Asakura NF13

Impact of divertor geometry: Long-leg divertor

- ***Peak power load* decreases from 16 to 12 MWm^{-2} in full detached divertor:**
  - *plasma heat load* decreases ← decrease in Ti
  - *Radiation load* decreases ← move of radiation peak
  - *surface recombination* and *neutral flux* increase,
    which may be caused by **small flux expansion**.

Long leg divertor is a possible approach to reduce the power load.

Further study for more appropriate geometry is in progress.



Toward further reduction of the target heat load

One of the possible solutions for further reduction of q_{target} is **change of machine specifications**, such as a fusion power P_{fus}, machine size, etc.

In addition, it is **difficult to extrapolate large f_{rad} 92%** from the present experiments accompanied by the energy confinement degradation and fuel dilution appropriate for the DEMO plasma.

Impact of fusion power and impurity seeding are investigated by SONIC V3

SONIC suite from V2 to V3

Mainly, impurity transport model has been improved.

- **backflow model** to reduce the impurity MC calculation time, which takes into account the impurity exhaust process in advance.
  → Full time-scale calculation from limited time-scale (50ms)
- **time averaging of Impurity MC calc.** to reduce large oscillation
  → improvement of charge neutrality

Following 3 cases are compared.

a) **P_{in}=500MW** (P_{fus}=3GW), **f_{rad}=92%**
b) **P_{in}=320MW** (P_{fus}=2GW), **f_{rad}=92%**
c) **P_{in}=320MW** (P_{fus}=2GW), **f_{rad}=80%**

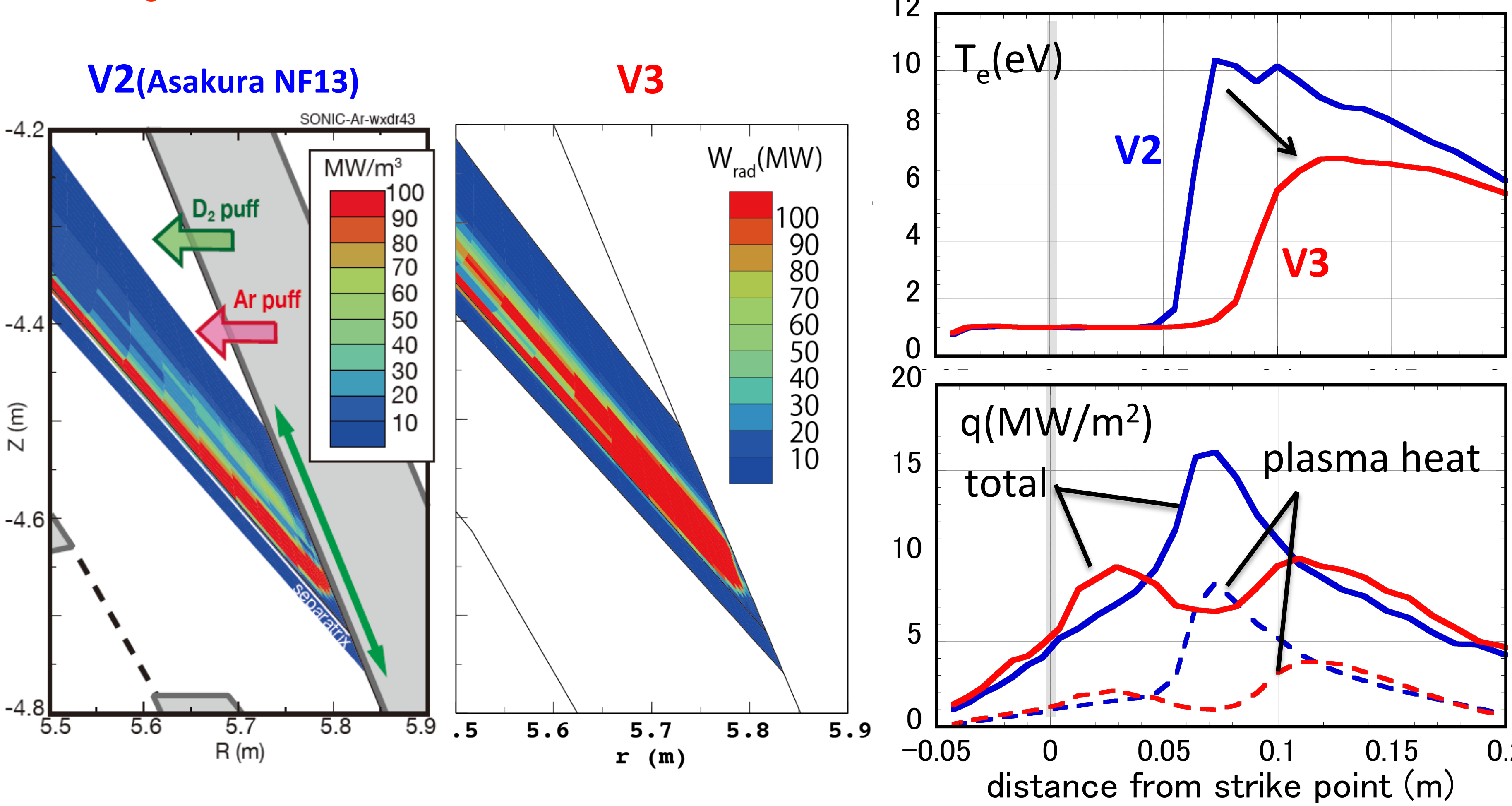
Comparison between SONIC V2 and V3

impurity radiation region becomes wide

due to improvement of the impurity transport model.

→ Peak T_e decreases from 10eV to 7eV, detached region is extended 5cm → 7cm.

→ **q_{target} decreases to 10MW/m^2 mainly due to decrease in plasma heat load**



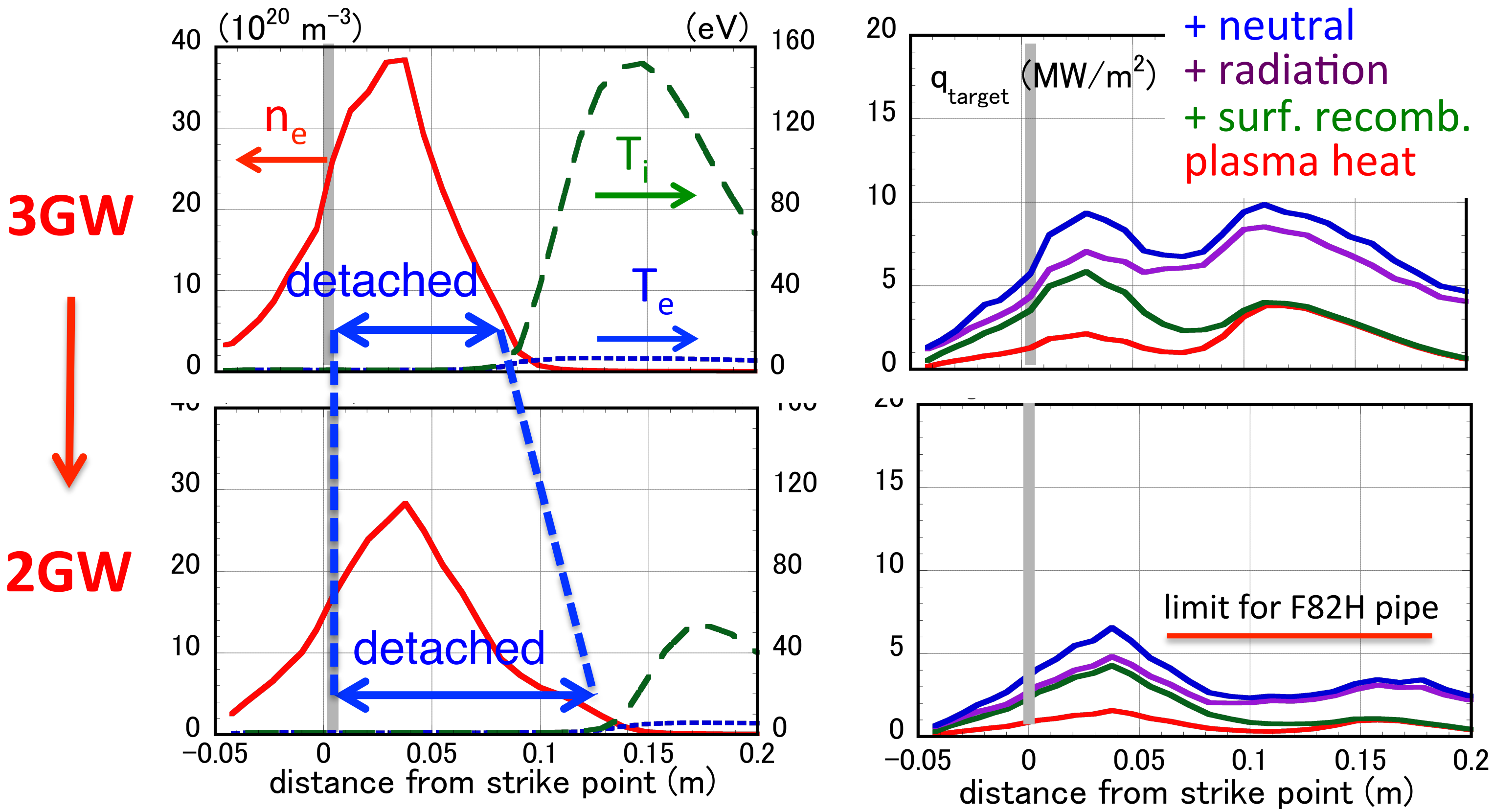
Impact of exhausted power (fusion power)

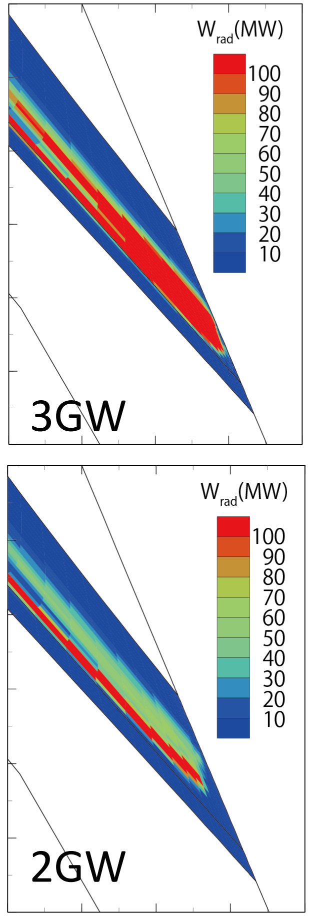
The peak target heat load is decreased to 6MW/m^2
by decrease in P_{fus} to 2GW (P_{in}=500 → 320MW).

f_{rad} ~ 92% (P_{rad}~295MW) is achieved by Ar puff of 10 Pa m^{-3} /s

Recycling is enhanced by low P_{fus}, and the **detached region is extended to 12cm**.

→ **Impurity radiation region moves upstream and the plasma heat load decrease at outer flux region.**





Impact of impurity radiation fraction

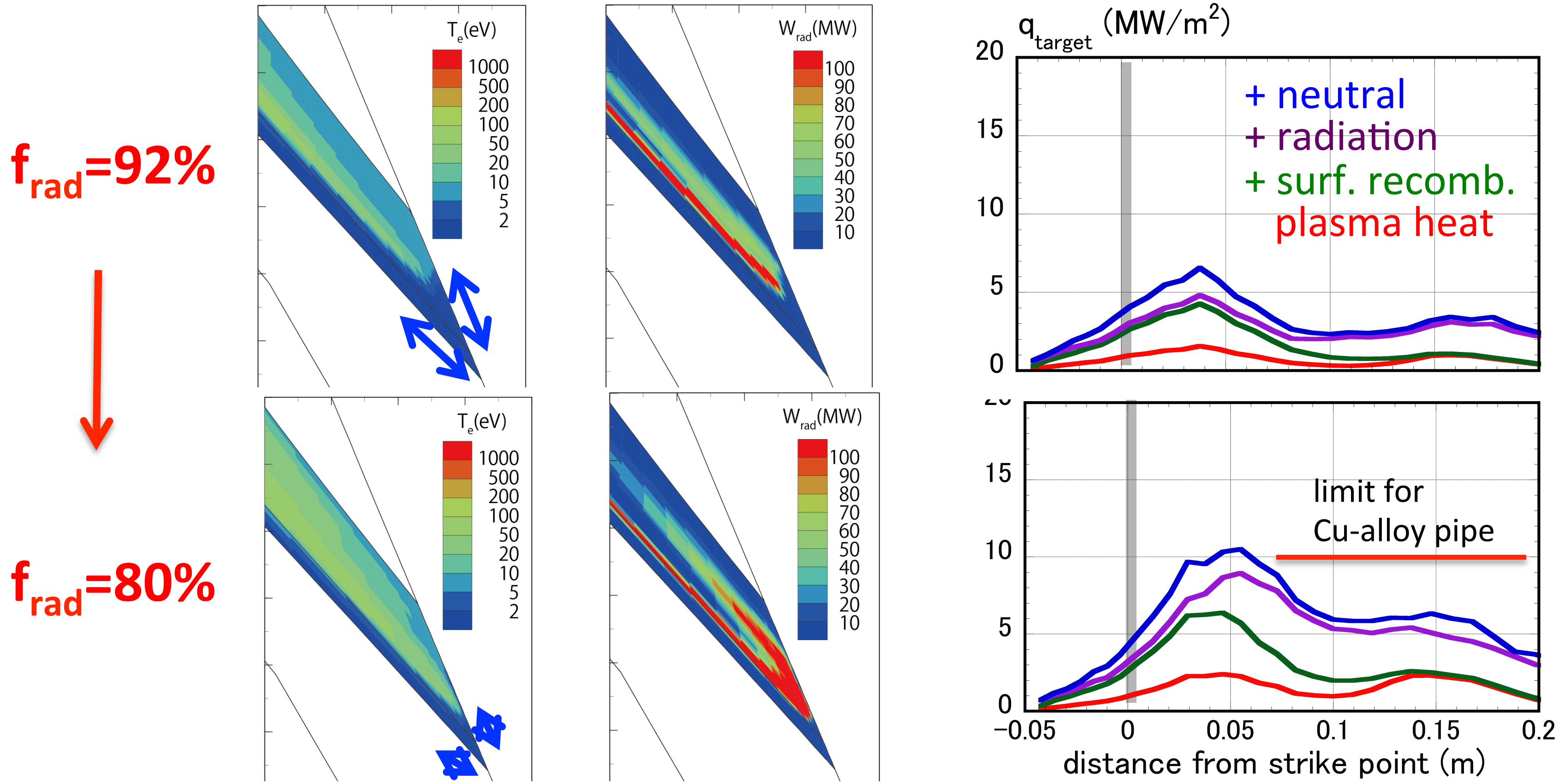
High f_{rad} with the high performance burning plasma is challenging issue.

f_{rad} can be reduced to 80%(256MW) at P_{fus}=2GW for Cu-alloy cooling tube

Detachment becomes weak poloidally due to smaller P_{rad} along the separatrix.

→ **Large radiation region moves to target and q_{target} increases to 10MW/m^2.**

To reduce f_{rad}, efficiency enhancement of the detachment is necessary, such as, divertor geometry, magnetic configuration, etc.



Divertor simulation for R_p~ 8m, P_{out} = 320 MW

SONIC simulation of the divertor plasma in the new Demo design with reduced P_{fus}:
large radiation loss case (f_{rad}=92%) showed that full detached was enhanced.
⇒ thermal instability of the divertor plasma occurs.

Calculations of lower radiation cases (f_{rad} = 70-85%) are now in progress.

Input parameters are the same

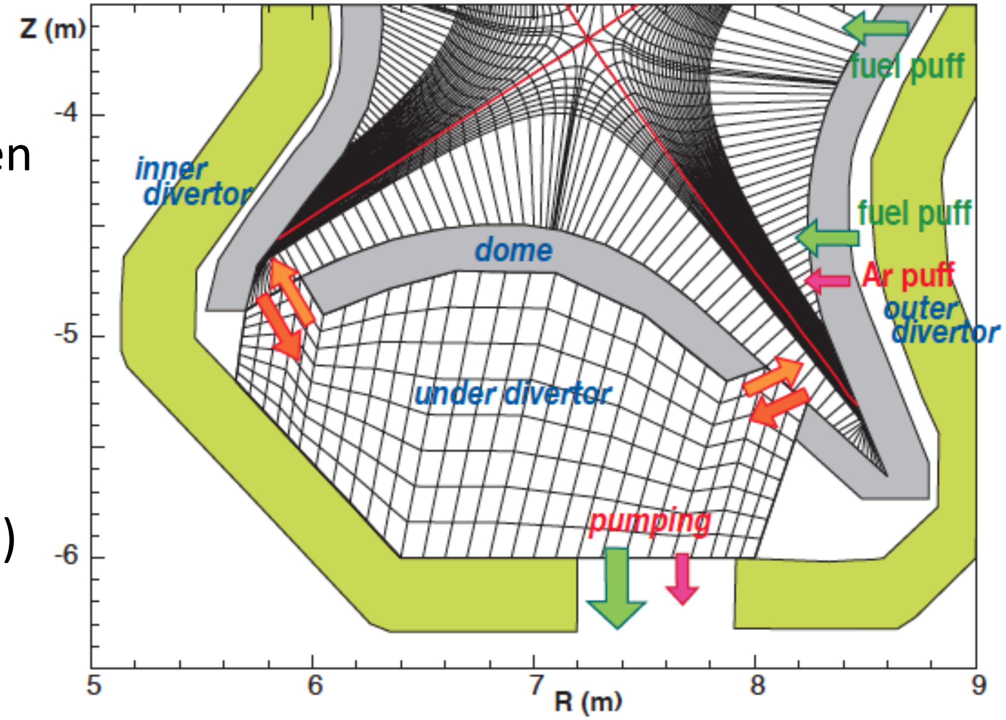
At core boundary r/a~0.95:

Exhausted power from core P_{out} is given
n_{D+}=7.0x10^{19} m^{-3}

Transport coeff. (same as ITER calc.):
D=0.3m^2/s, χ=1.0m^2/s

D gas puff: Γ_{puff}=0.8x10^{23} s^{-1} (div. + sol)

pumping speed: S_{pump}=200 m^3/s



Engineering and Physics studies for advanced divertor

Recently, advanced divertor concepts have been proposed:

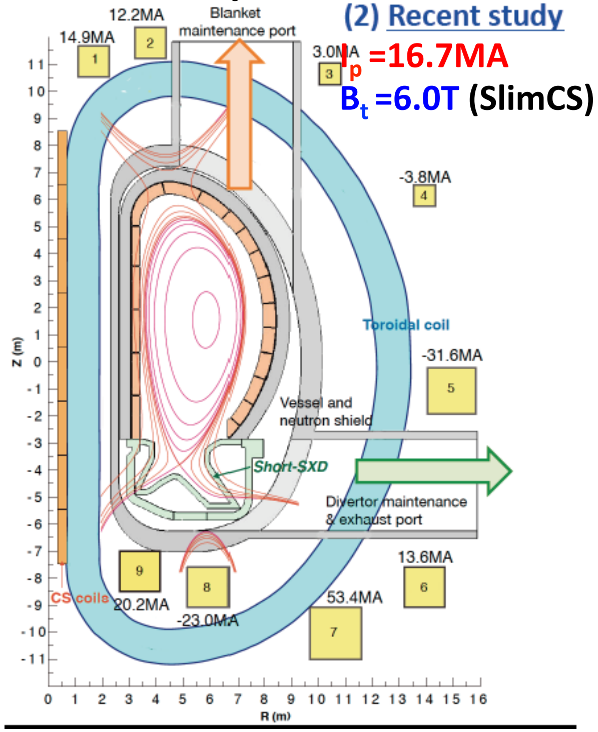
Super-X divertor, short super-X divertor, snowflake divert

Divertor leg and target area are increased to reduce T_e^{div} and q_{target}.

$T_{div} \propto q_{//}^{10/7}/(n_u^2 L_{//}^{4/7})$ (from 2-point model)

$A_{wet} = [B_p/B_t]_{sol}\ [R_{div}/R_{sol}]\ A_{sol}/\sin\theta$

example of coil arrangement for short super-X

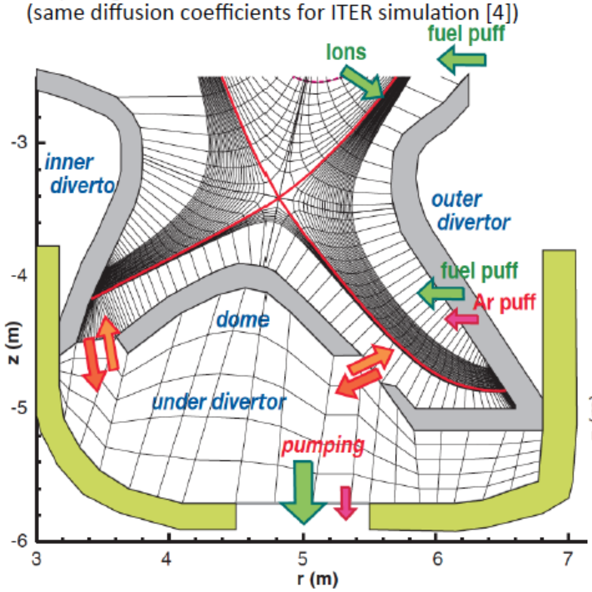


Input parameters:

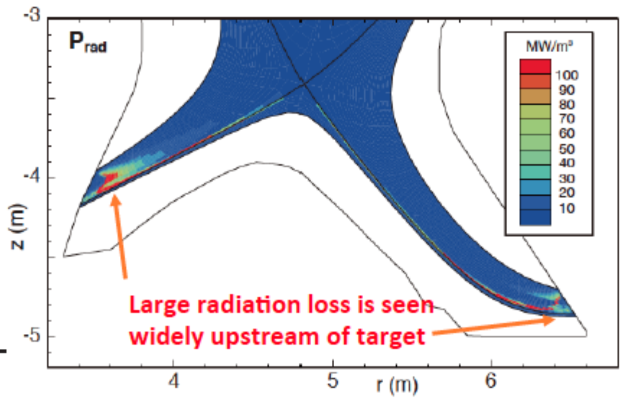
P_{out} = 500 MW, n_e=7x10^{19} m^{-3} (r/a=0.95),

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

(same diffusion coefficients for ITER simulation [4])



First example (f_{rad} =0.92) shows Full detachment (T_e~ T_i = 1-2eV) is produced at both divertors.



Summary

DEMO divertor design study, especially, the huge power handling, has been progressed by using SONIC.

- ✓ The heat removal capability of the DEMO divertor target is
  4-7 MW/m^2 for RAFM cooling pipe and 10MW/m^2 for Cu-alloy cooling pipe.
- ✓ The partial detached divertor was obtained by the large impurity radiation (92% of P_{out}).
  However the divertor power load is still larger than max. q_{target}.
- ✓ Selection of impurity species and geometry optimization are possible approach to reduce the target heat load.
- ✓ Investigation of operational window from the viewpoint of the divertor design started.
- ✓ Impacts of the machine specification and the advanced divertor concept are also under investigation.

The huge power handling in DEMO divertor is still open issue, but SONIC show a possible approach to solve the power handling issue.