Design of the multi configuration DTT divertor by edge modelling with SOLEDGE2D

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FSD Science Coordination Meeting on edge and PWI modelling in I-DTT
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The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Summary

- Requirements, assumption, constraints and fundamental choices
- Development of divertor shape
- Comparison with reference standard shape
- Compatibility with pumping
- Analysis of different effects
- Preliminary conclusions

Requirements and Assumptions

- Compatible with following magnetic configurations: **SN, XD and NT (not a priority)**
- **Compatibility with the PF coil system**, power supply and controllability
- Flexible for experimental exploitation at plasma relevant parameters ➔ wide range in terms of X-point and strike points positions
- Full power operation (P_{ADD}=45 MW) with about 1/3 of the power dissipated in the core (based on core modeling)
- Density control by gas-puffing and pumping **(negligible core particle flux from NBI)**
- Power crossing separatrix higher than minimum requested for H-mode operation in positive triangularity **(no X-point radiation configuration)**

❑ ELMs not considered in modeling but average ELMs power (5 MW) subtracted from stationary heat flux

❑ Transport in agreement with Eich scaling with radial profiles as in present devices

Constraints and fundamental choices

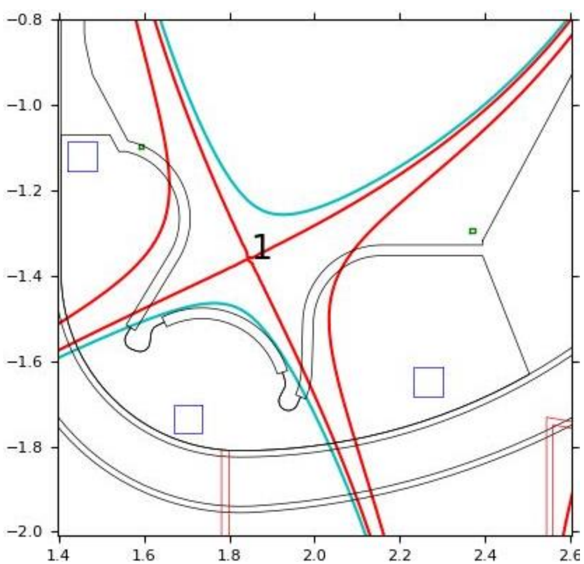
- All PFUs (IVT,OVT and DOME) are in **tungsten actively cooled**
- **Minimum bending radius** (of the plasma facing surface in W) **~ 190 mm** - manufacturing constraint
- **Cooling pipes must be shielded** from parallel plasma heat flux and possible strike points movements

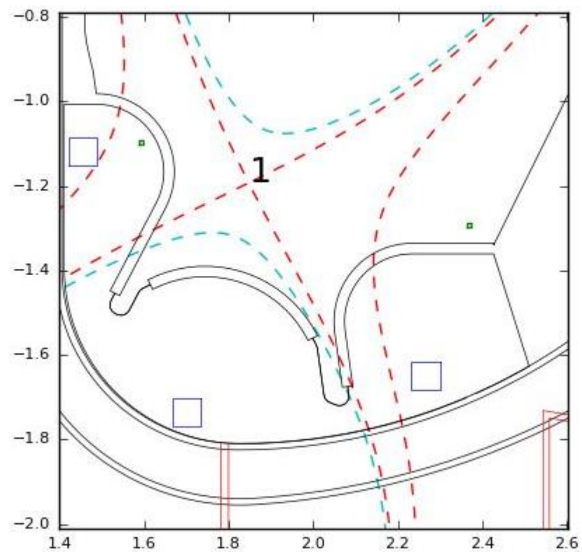
- Inner board and outer board **grazing angle 2°** for reference SN configuration, smaller angle possible for XD configuration
- Dome can accommodate strike points
- **Pumping speed 100 m^3/s** and pumping slots between vertical targets and "central dome"

From divertor shape definition to optimization

1. **Definition of different divertor shapes compatible with constraints and fundamental choices**
2. **Definition of reference (and additional) magnetic configurations**
3. **Selection by comparison between shapes and a reference standard shape**
4. **Divertor shape optimization**

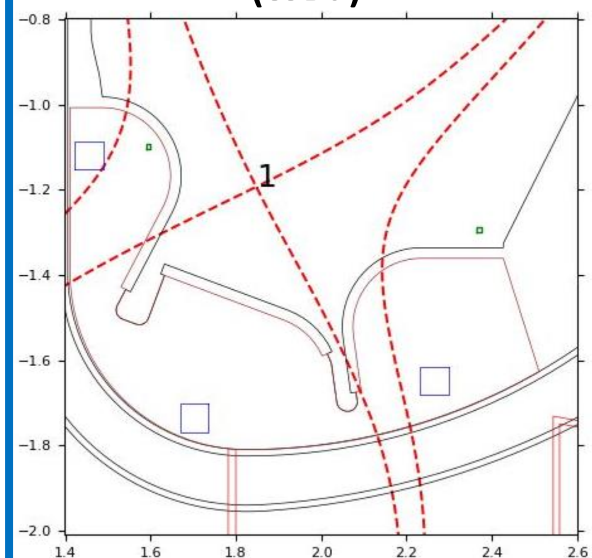
Standard divertor (SD)



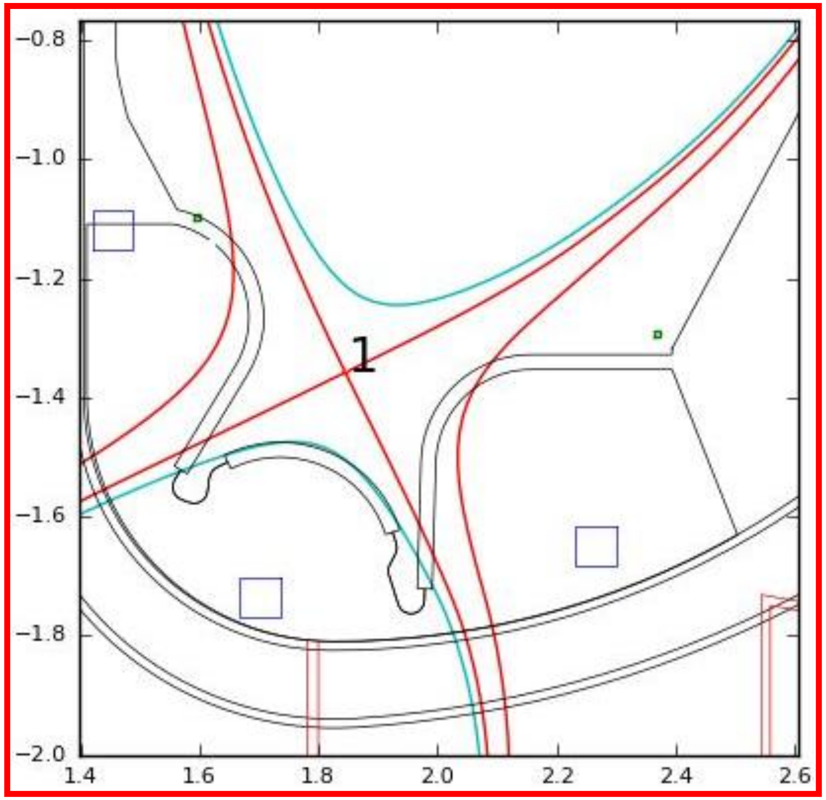


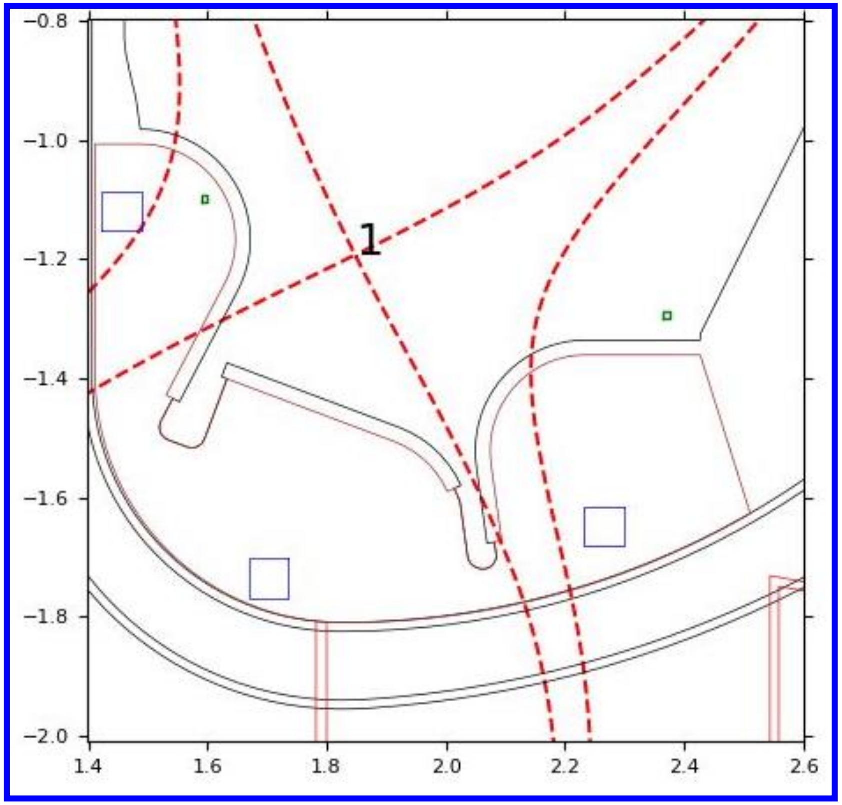
Wide divertor (WD)

Wide divertor with flat-dome (WDF)



Base configurations: SN @ 5.5 MA





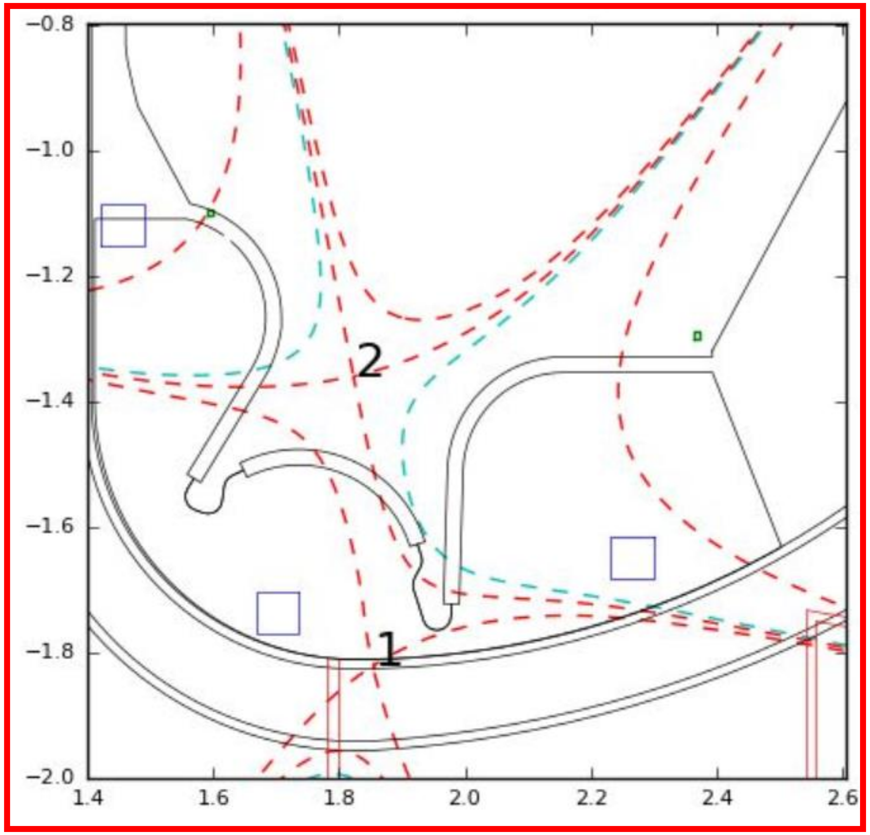
Grazing angles:
IT = 2.0°
OT = 1.9°

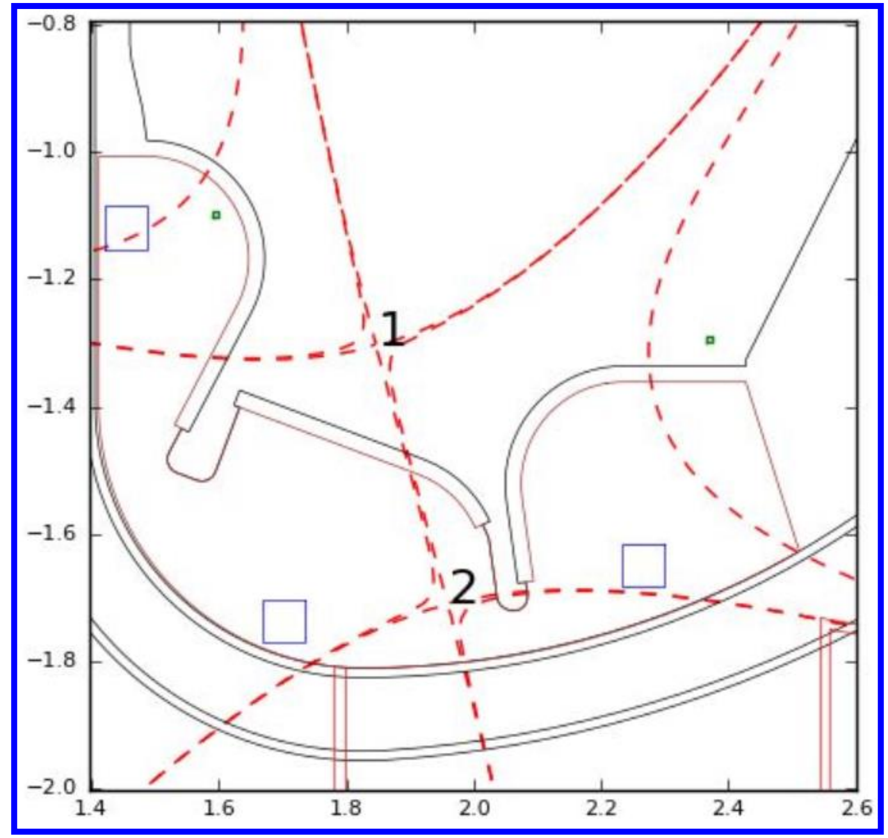
Legs lengths:
L_{IT} = 26 cm ➔ $L_{IT}/Rx=0.14$
L_{OT} = 28 cm ➔ $L_{OT}/Ro=0.15$

Grazing angles:
IT = 2.0°
OT = 2.0°

Legs lengths:
L_{IT} = 25 cm ➔ $L_{IT}/Rx=0.14$
L_{OT} = 46 cm ➔ $L_{OT}/Rx=0.25$

Base configurations: XD @ 4.5 MA





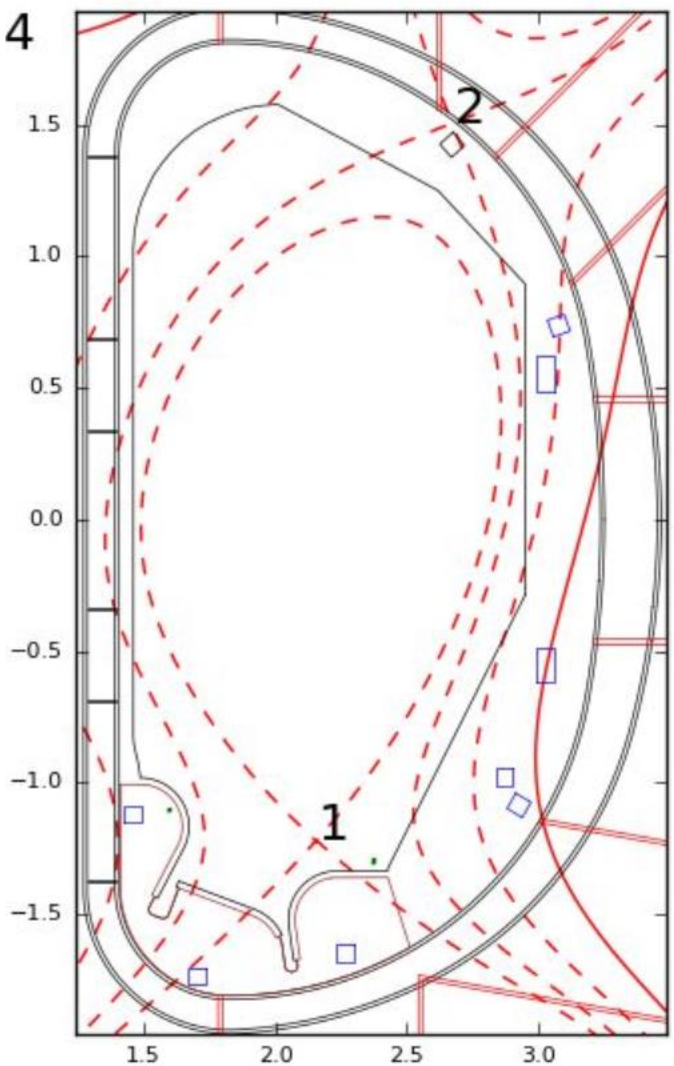
Grazing angles:
IT = 0.6°
OT = 0.2°

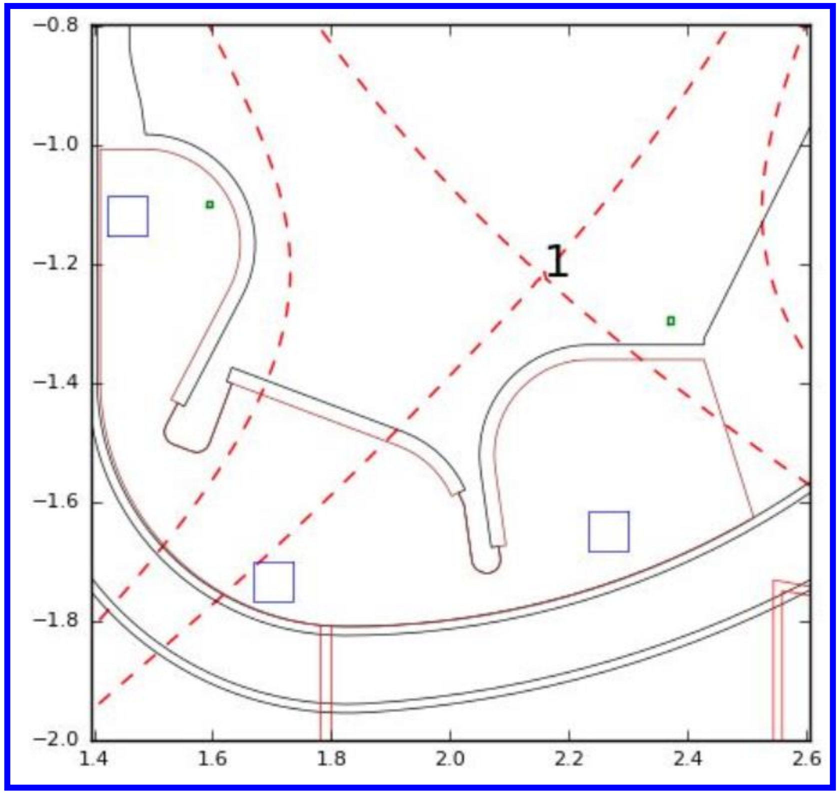
Legs lengths:
L_{IT} = 17 cm ➔ L_{IT}/Rx=0.09
L_{OT} = 20 cm ➔ L_{OT}/Rx=0.11

Grazing angles:
IT = 1.0°
OT = 0.3°

Legs lengths:
L_{IT} = 24 cm ➔ L_{IT}/Rx=0.13
L_{OT} = 16 cm ➔ L_{OT}/Rx=0.09

Additional configurations: NT @ 4.0 MA

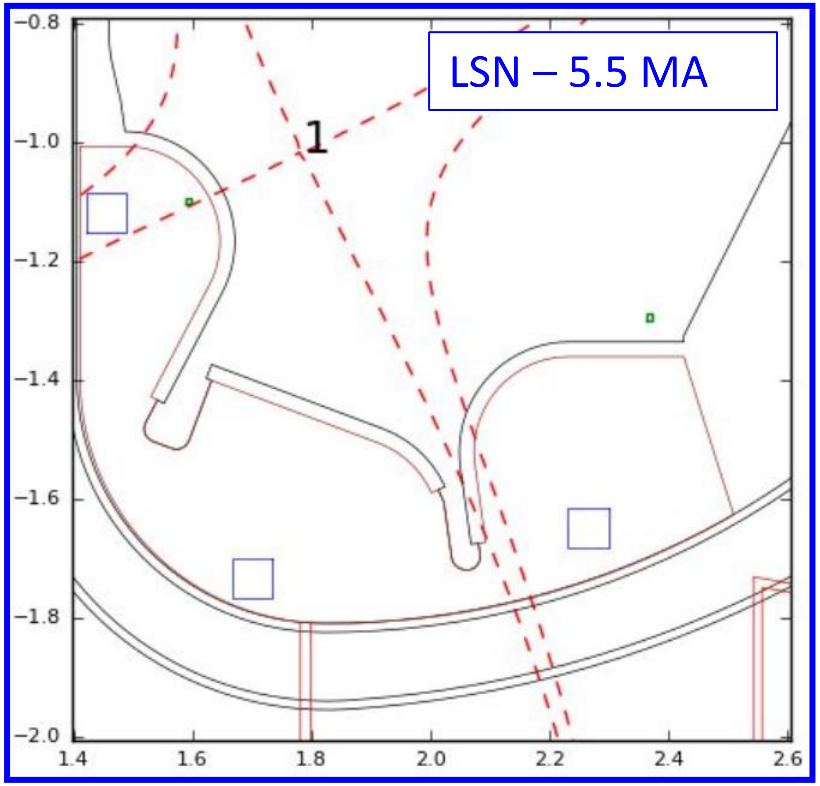


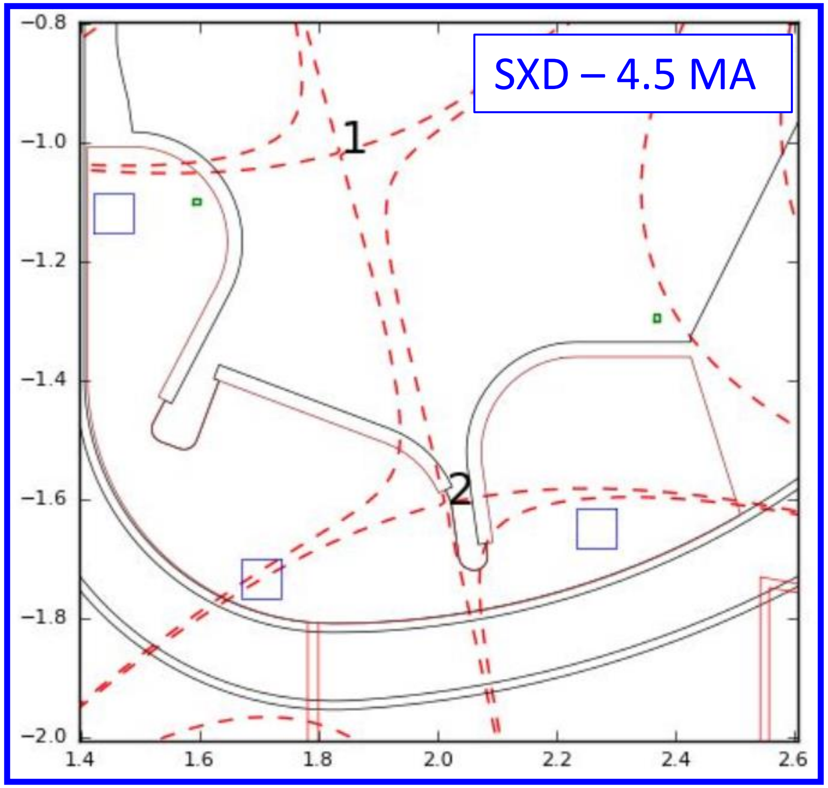


Grazing angles:
IT = 3.4°
OT = 1.4°

Legs lengths:
L_{IT} = 36 cm ➔ L_{IT}/Rx=0.20
L_{OT} = 18 cm ➔ L_{OT}/Rx=0.10

Additional configurations: long leg SN & XD (SXD)





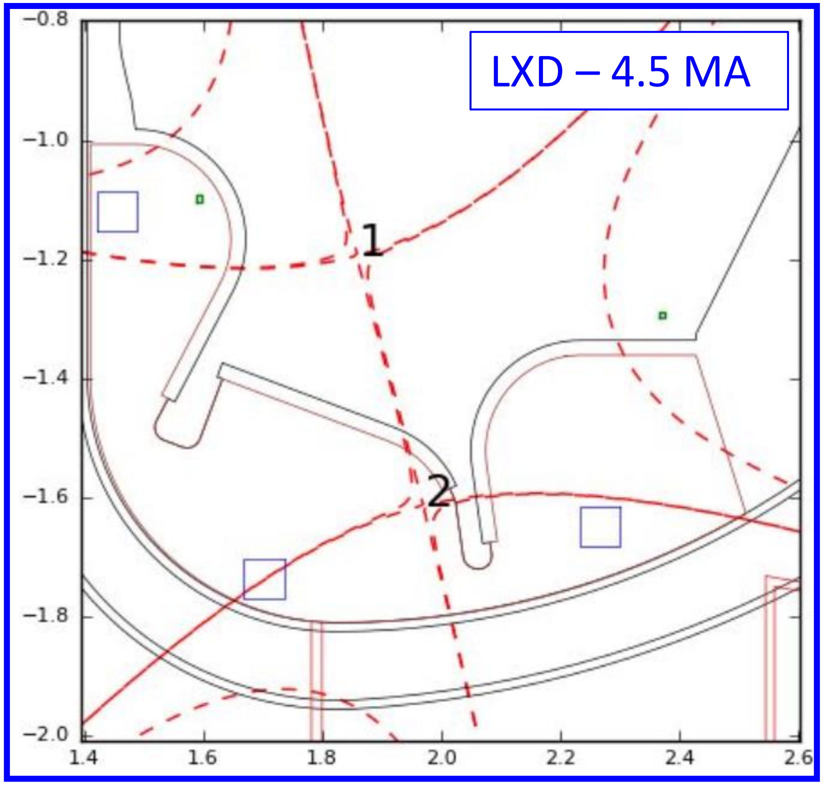
Grazing angles:
IT = 1.7°
OT = 2.2°

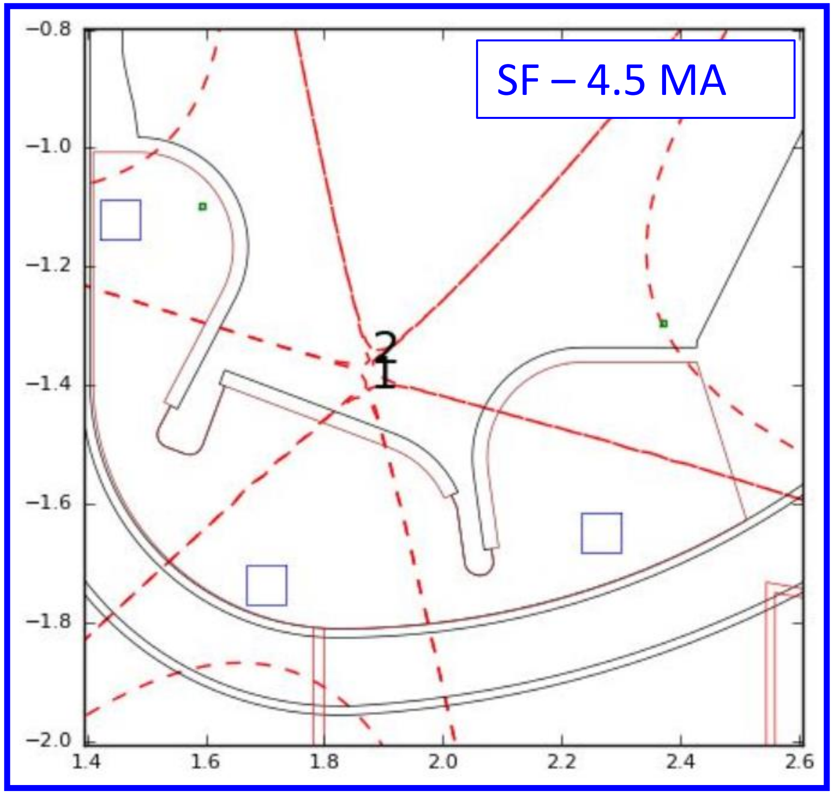
Legs lengths:
L_{IT} = 14 cm ➔ L_{IT}/Rx=0.08
L_{OT} = 63 cm ➔ L_{OT}/Rx=0.34

Grazing angles:
IT = 1.2°
OT = 0.5°

Legs lengths:
L_{IT} = 20 cm ➔ L_{IT}/Rx=0.11
L_{OT} = 46 cm ➔ L_{OT}/Rx=0.25

Additional configurations: longer leg XD and SF





Grazing angles:
IT = 1.0°
OT = 0.4°

Legs lengths:
L_{IT} = 19 cm ➔ L_{IT}/Rx=0.10
L_{OT} = 29 cm ➔ L_{OT}/Rx=0.15

Snowflake configuration to be optimized ➔ not modeled

Divertor parameters

SN configuration

Device	L_{IT}/Rx	L_{OT}/Rx	a_{IT}	a_{OT}
DTT (SD)	**0.09-0.15**	**0.15-0.17**	**2.0°**	**1.9°**
DTT (WDF)	**0.07-0.14**	**0.24-0.34**	**1.6°-2.0°**	**2.0°-2.3°**
DEMO	0.15	0.21	1.5°	1.6°
ITER	0.19	0.20	3.2°	2.7°
JT-60SA	0.21	0.29	5.6°	3.5°

- Standard divertor is similar to **(present)** DEMO divertor in terms of **legs length** and **grazing angle**
- Wide divertor can test a **wide range of leg lengths**
- In general grazing angle is in between ITER and DEMO

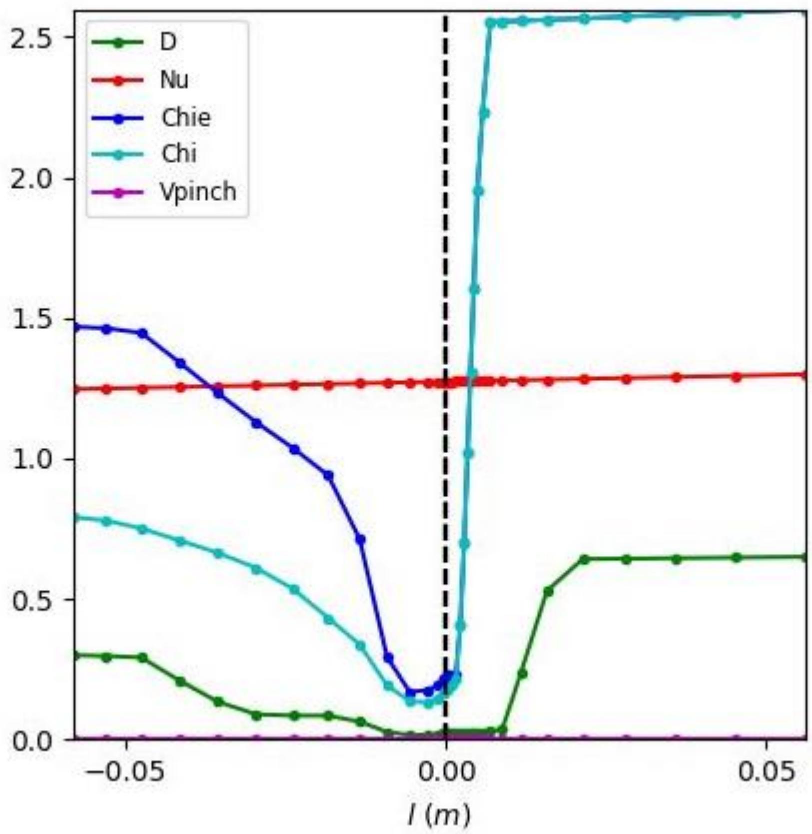
XD configuration

Device	L_{IT}/Rx	L_{OT}/Rx	a_{IT}	a_{OT}
DTT (SD)	**0.09-0.11**	**0.11-0.14**	**0.6°**	**0.0-0.2°**
DTT (WDF)	**0.10-0.11**	**0.10-0.25**	**1.1°-1.2°**	**0.3°-0.6°**

Assessment of divertor performance

1. **Edge modeling of a representative set of magnetic configuration:**
   - SN in pure D power scan with P_{SOL}=3.5÷25 MW with five different divertors and different transport parameters and with sub-divertor modeling
   - XD in pure D power scan with P_{SOL}=3.5÷8 MW with five different divertors
   - NT in pure D power scan with P_{SOL}=4÷8 MW with three different divertors
   - SN scan in neon and argon seeding at full power P_{IN}=30 MW with four different divertors and different transport parameters (a few cases), with sub-divertor and variation in trasport parameters
   - XD scan in neon seeding at full power P_{IN}=30 MW with four different divertors
   - NT scan in neon seeding at full power P_{IN}=30 MW with two different divertors
2. **Comparison of performance with the standard divertor**
3. **Gas puffing and top pedestal density estimation**

Modelling methods and edge code



Transport profiles

1. Transport parameters based on **heat flux decay length $\lambda_{q,u}$≈1.5 mm** for the SN in attached condition and JET/C-Mod experiments modelling. **Equal for SN, XD and all divertor shapes**

2. Seeding with **neon** and **argon**

3. Fixed **pumping speed S=100 m^3/s** ➔ gas-puffing adjusted to achieve target separatrix density

4. Targets:
   - **same separatrix density**
   - **about same radiation (with seeding)**
   - **H-mode condition ➔ P_{SOL}≥18 MW**

5. SOLEDGE2D-EIRENE 2D edge fluid/kinetic code

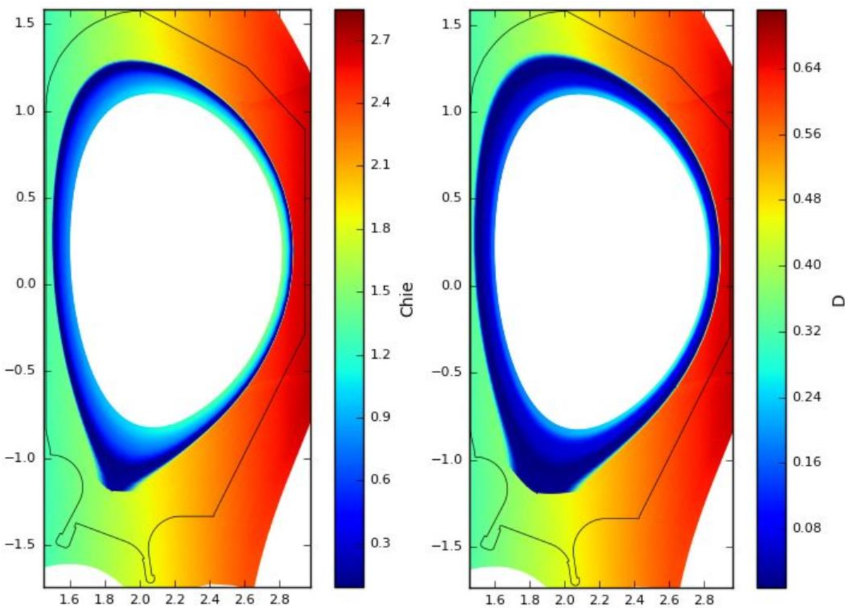
6. **Drifts not considered**

2D transport parameters map

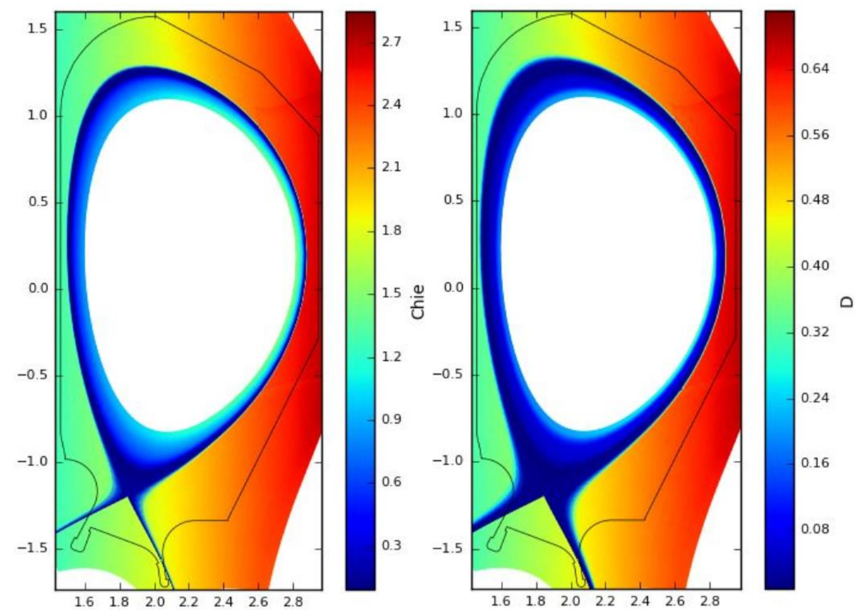
Transport parameters have been normalized to B_t

Two options for the divertor region:

1. Value as in the OMP far SOL (as in the JET/C-Mod modeling)
2. Values like at OMP



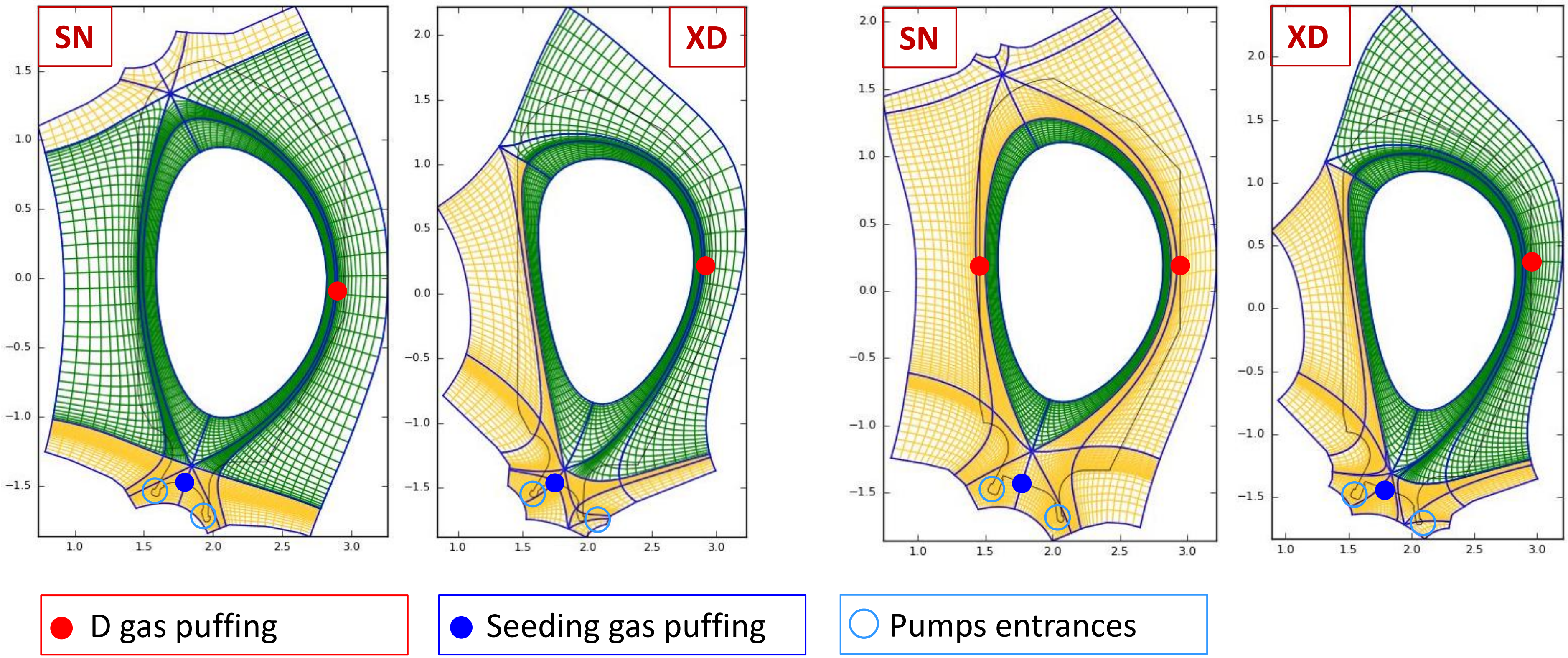
Transport in divertor region as at the OMP far SOL



Transport in divertor region like at OMP

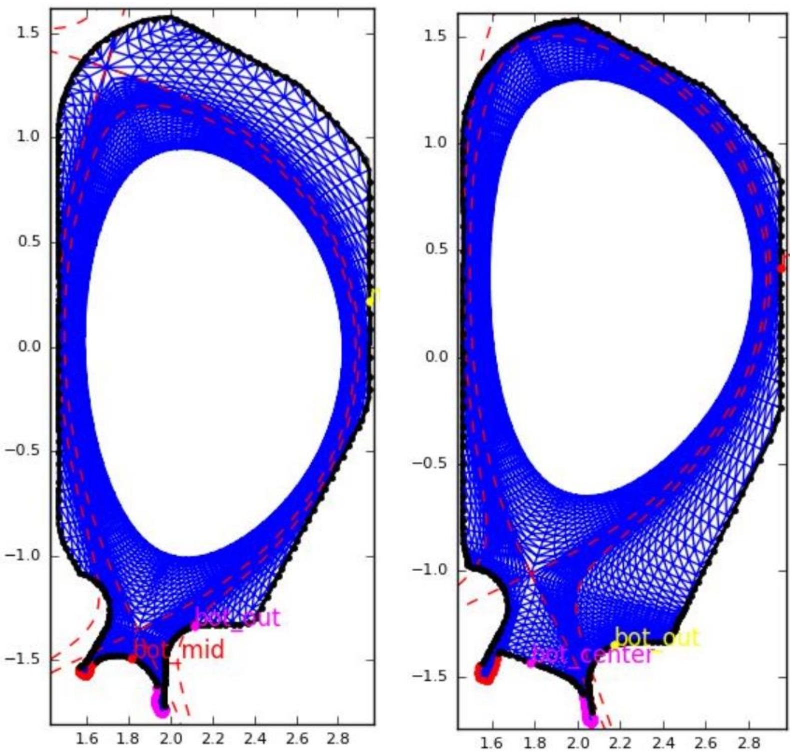
Fluid meshes for the base configurations

D gas puffing from outer mid plane, few cases also from high field side
Seeding always from top of the dome
Puffing adjusted to achieve separatrix density and detachment/radiation fraction



EIRENE mesh

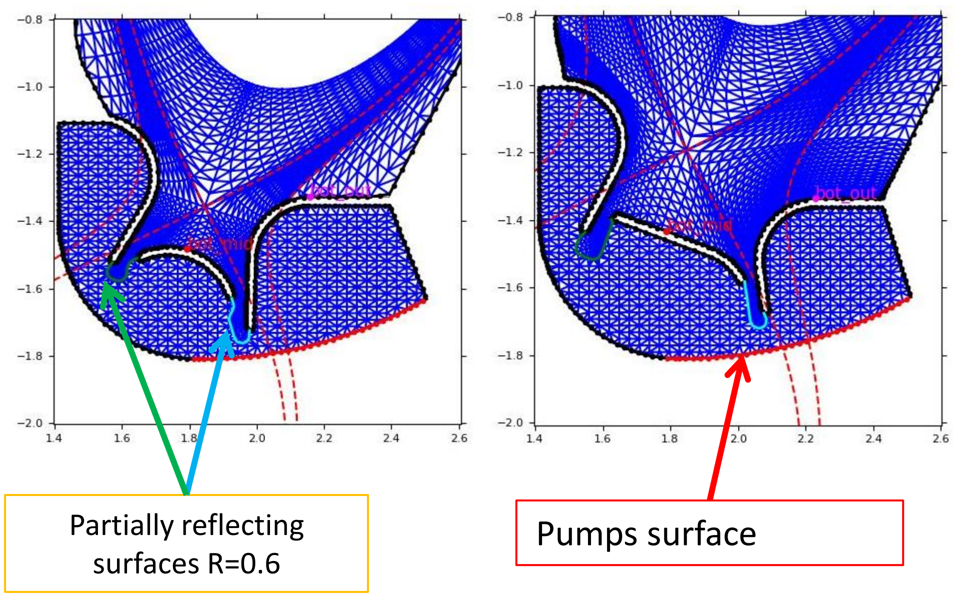
Standard EIRENE mesh on the plasma region



EIRENE mesh extended to the sub-divertor region

➔ To provide a better estimation of fluxes for:

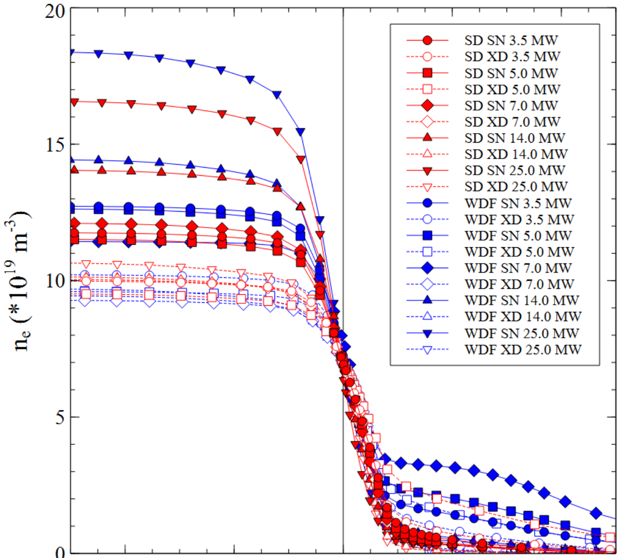
1. **for enrichment computation**
2. **pumping capability**

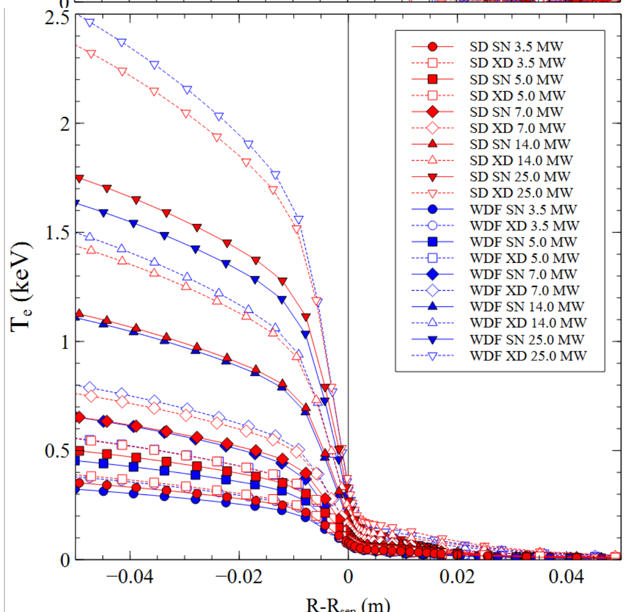


P_{SOL} scan in pure deuterium

- To provide an indication on allowed maximum heat flux for detachment
- To provide a starting point for seeded modeling
- To provide an indication on pumping efficiency

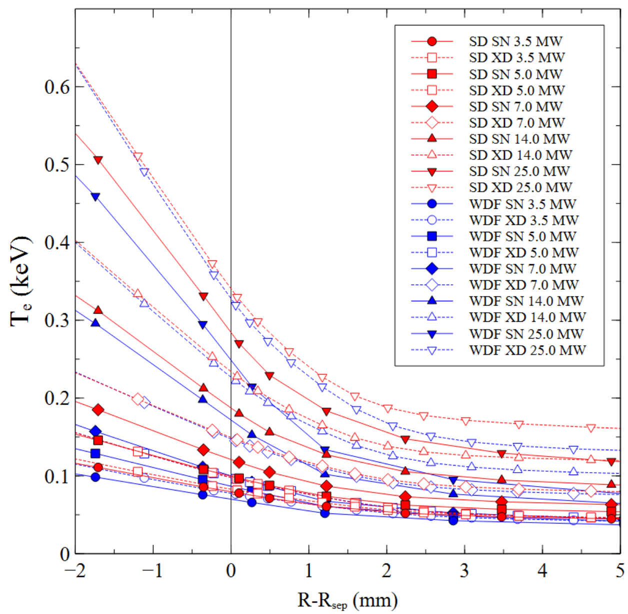
Profiles at outer mid-plane P_{SOL}=3.5-25 MW



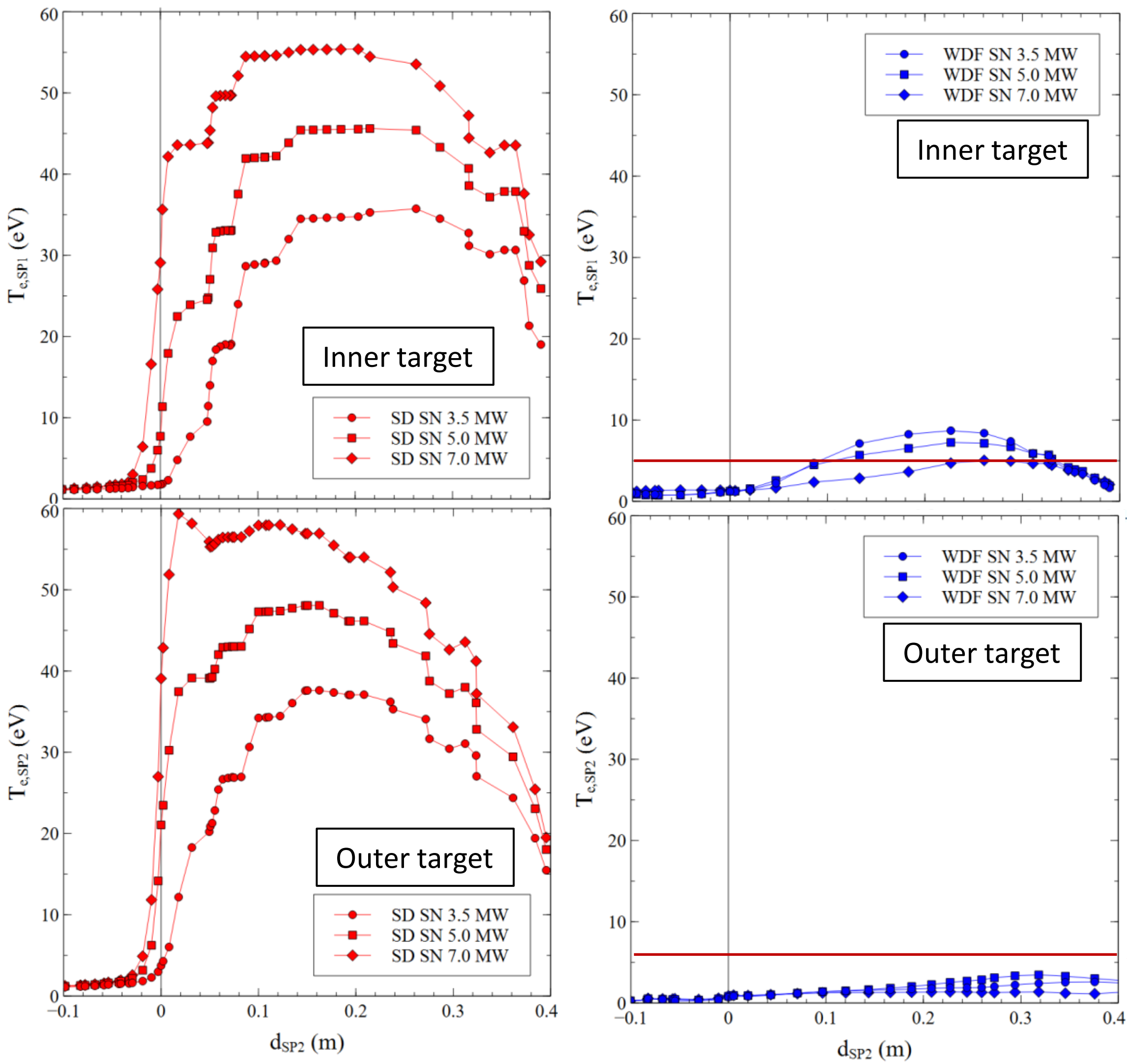


- **Same separatrix density**
- different top pedestal density (higher/lower pumping efficiency)

- Highest top density in SN
- Lowest density in XD ➔ low pumping efficiency due to strike points far from pumps slots
- Higher separatrix temperature in XD due to longer connection length



SN: profiles at targets



In pure D with the wide divertor detachment is obtained below P_{SOL}≈7 MW at $n_{sep}=7\cdot10^{9}\ m^{-3}$

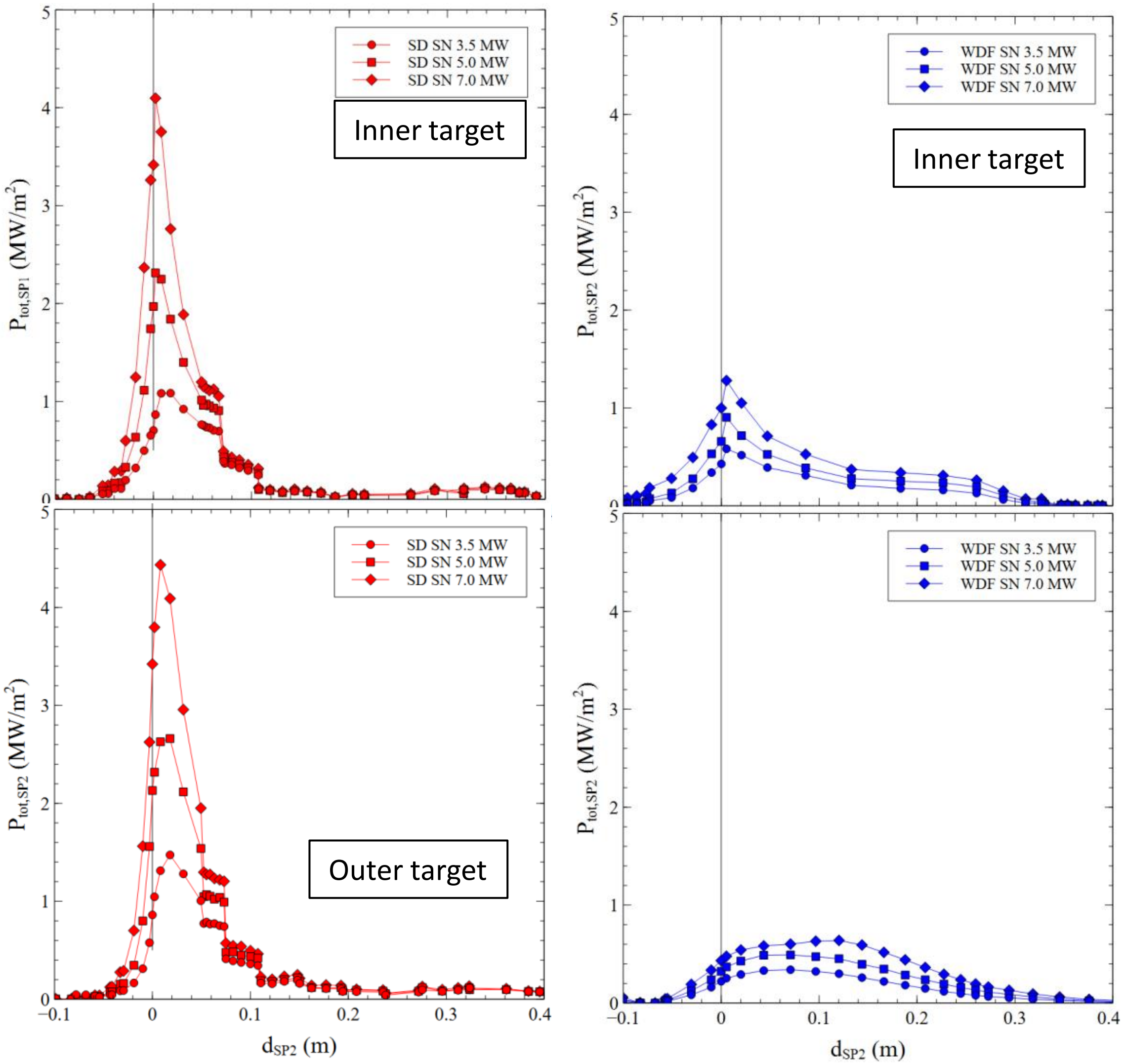
Peak heat flux is well below 10 MW

Similar conditions at both targets (but drifts not included)

The standard divertor provides word performance ➔ higher temperatures and peak heat fluxes

Detachment threshold

SN: profiles at targets



In pure D with the wide divertor detachment is obtained below P_{SOL}≈7 MW at n_{sep}=7·10^9 m^{-3}

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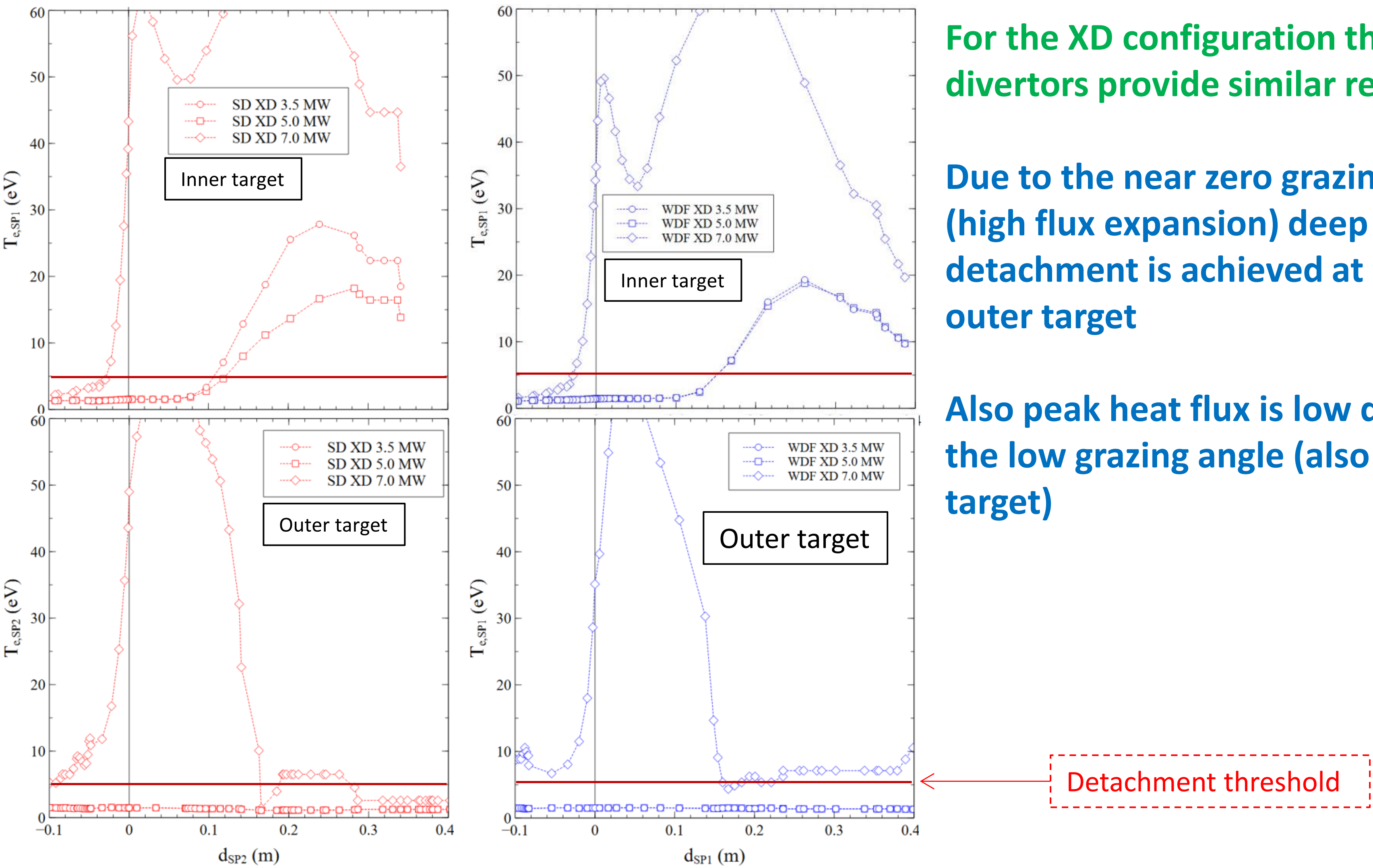
Similar conditions at both targets (but drifts not included)

The standard divertor provides word performance ➔ higher temperatures and peak heat fluxes

XD: profiles at targets

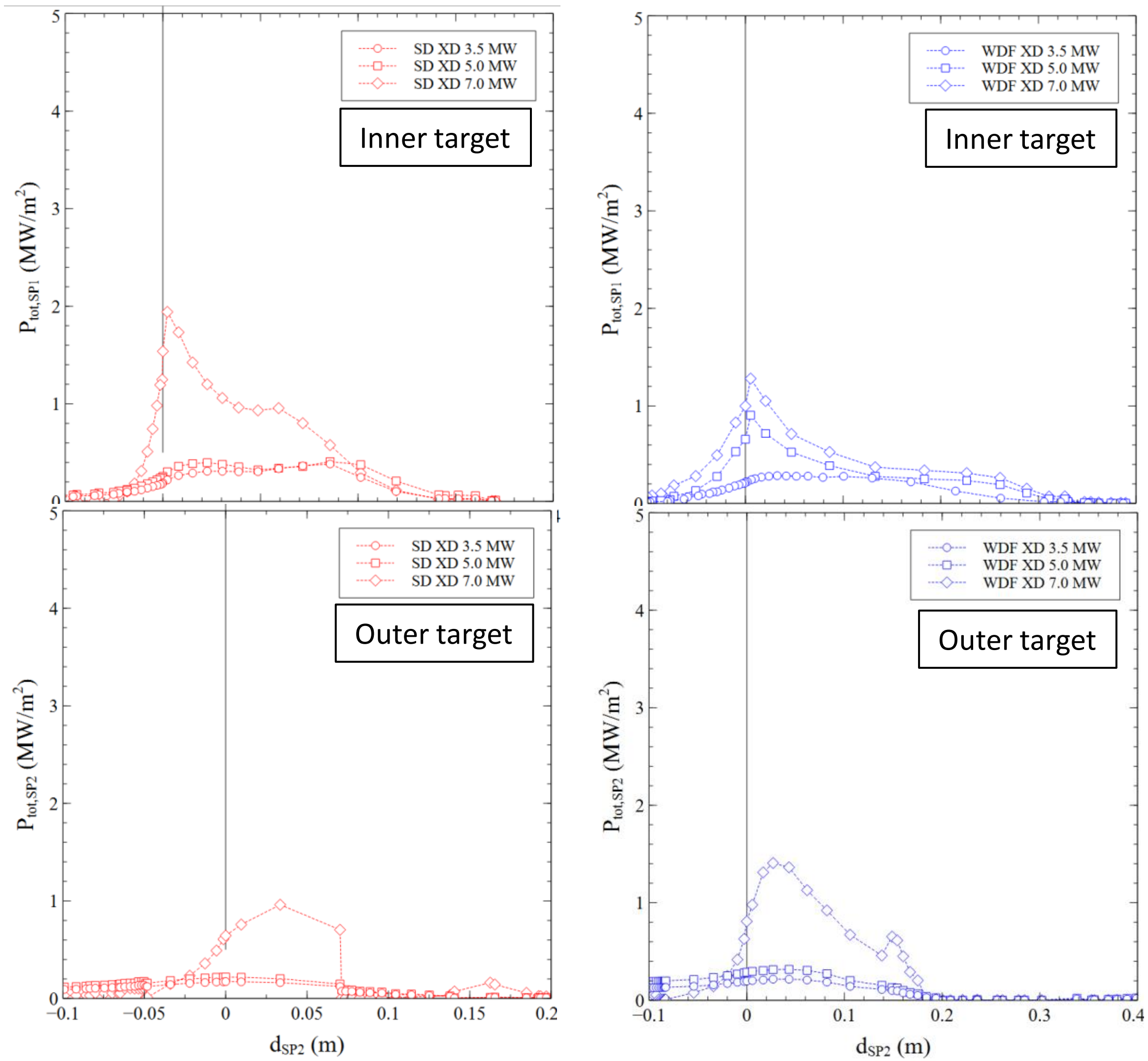


For the XD configuration the two divertors provide similar results

Due to the near zero grazing angle (high flux expansion) deep detachment is achieved at the outer target

Also peak heat flux is low due to the low grazing angle (also at inner target)

XD: profiles at targets



For the XD configuration the two divertors provide similar results

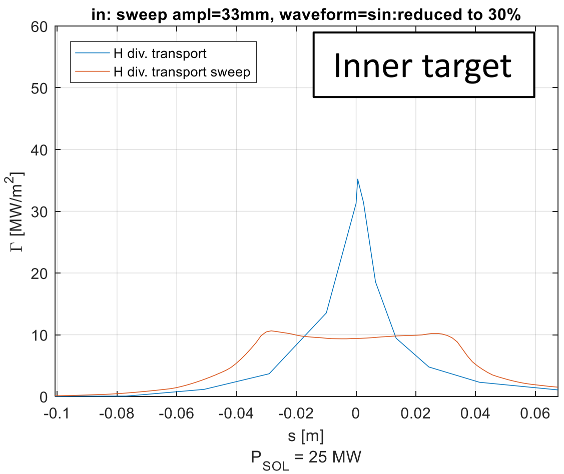
Due to the near zero grazing angle (high flux expansion) deep detachment is achieved at the outer target

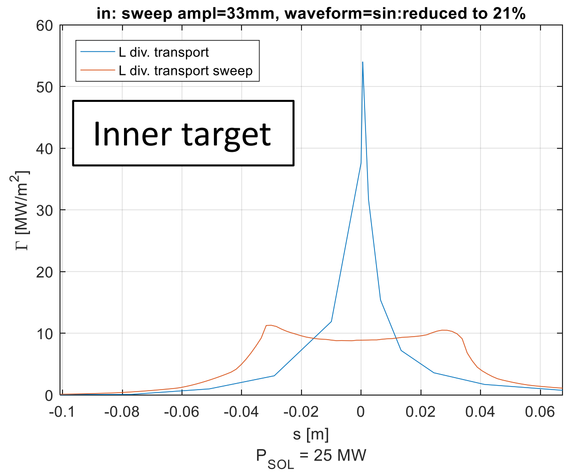
Also peak heat flux is low due to the low grazing angle (also at inner target)

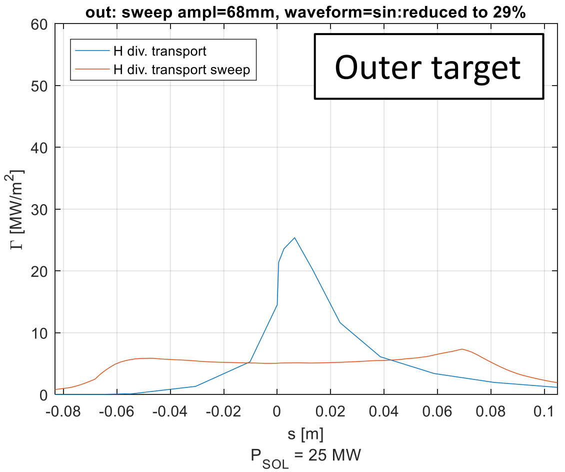
SN: targets without/with sweeping @ P_{SOL}=25 MW

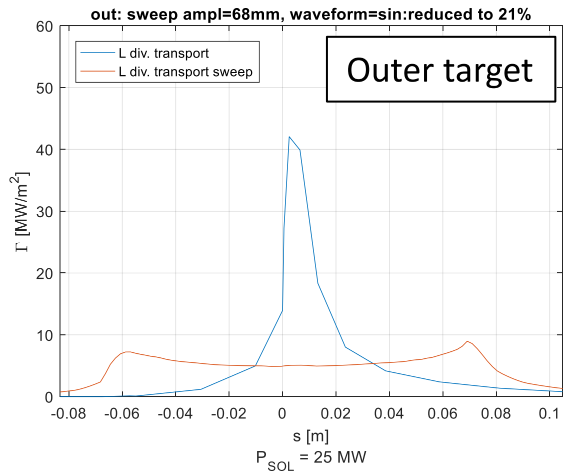
Testing save divertor operation in attached plasma by sweeping

Edge modeling with very low transport parameters corresponding to λ_q≈0.8 mm









- Analyses carried out with **two different transport assumptions** so as to test the most critical conditions expected in DTT in terms:
  - H: transport in the divertor region like in the far-SOL
  - L: transport in the divertor region like at the midplane

➢ **Peak heat flux up to 50 MW**

➢ **Very narrow heat flux distribution**

In all cases heat flux reduced to/below 10 MW with sweeping

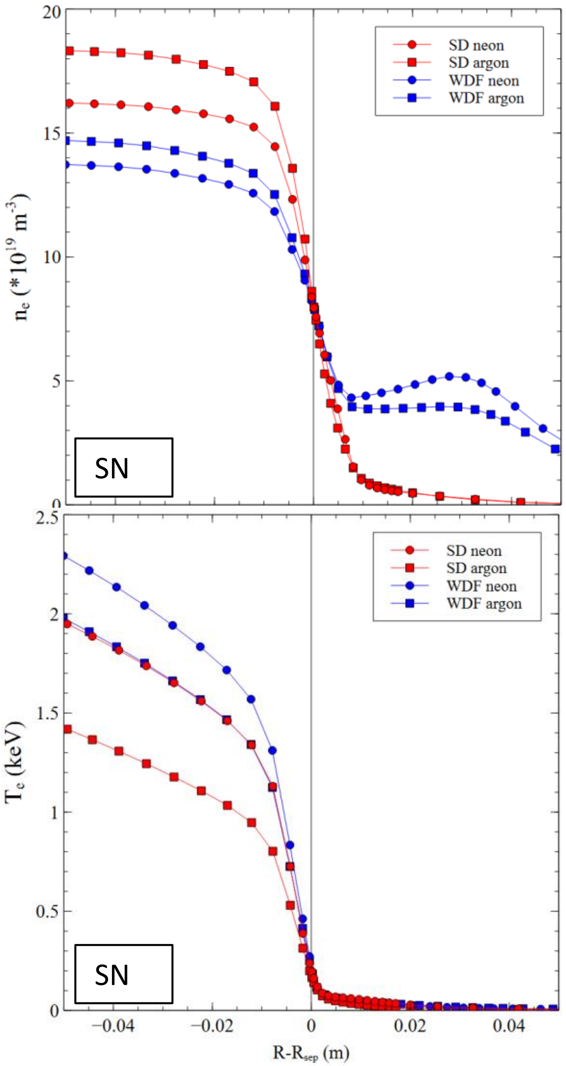
➔ Safe operation at very high power

Operation at full power with seeding

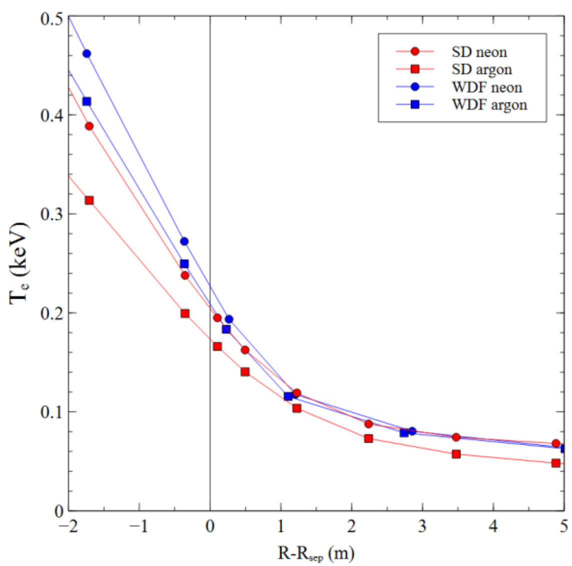
- Evaluated minimum requested contamination to achieve detachment
- Evaluated operative window in impurity content
- Configuration stability against operating condition

Seeding at full power

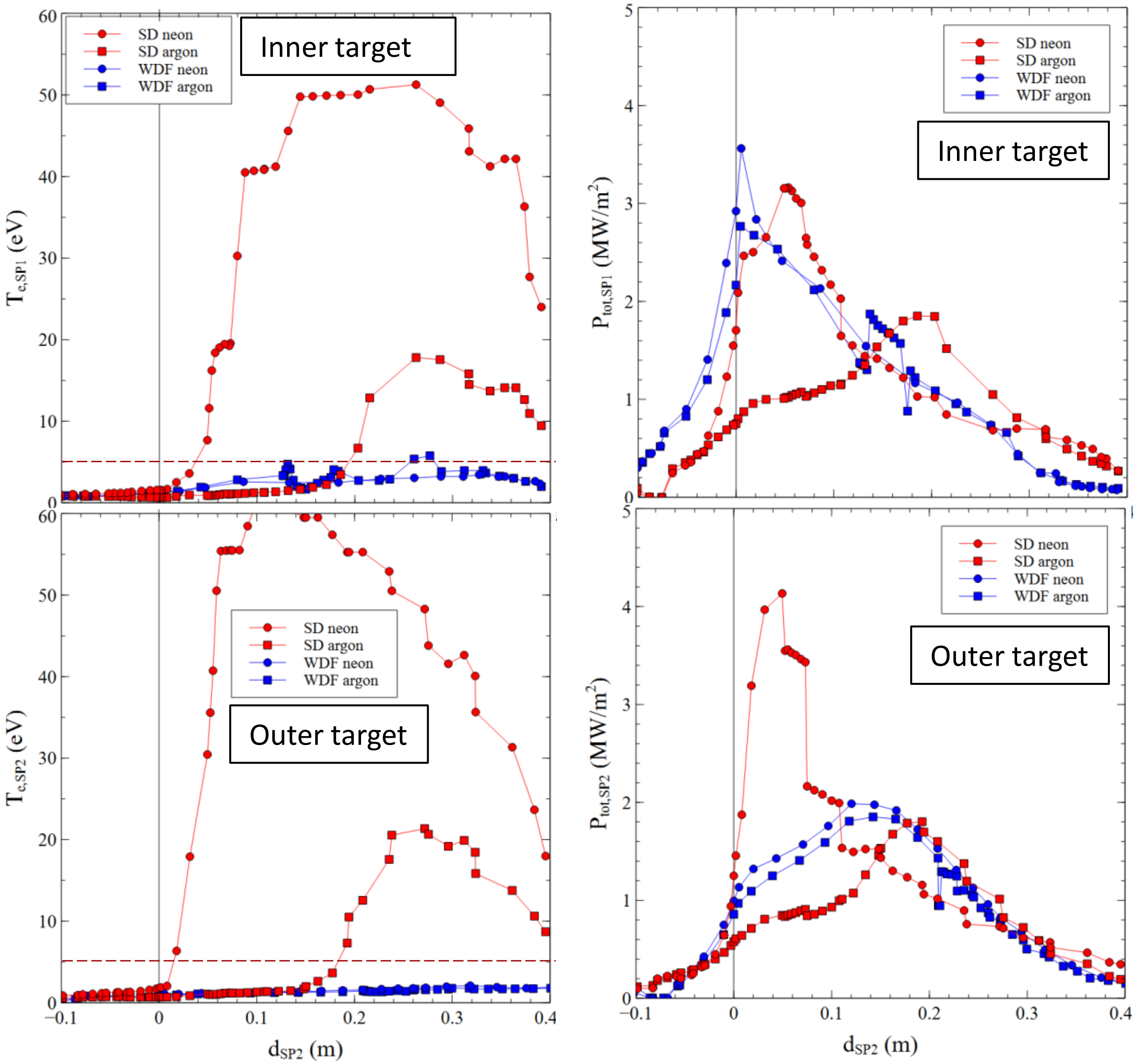
- P_{IB} = 30 MW (10 MW rad. in the inner core, 5 MW ELMs)
- P_{IB} splitted between e and D to achieve similar temperatures
- $n_{sep}=8\cdot10^{19}$ m^{-3}
- $P_{SOL}=P_{IB}-P_{rad,in}$ **(must be > 18-20 MW to access H-mode)**



- Higher core density with argon
- Higher core temperature with neon
- Higher temperature at separatrix with neon (related to Ne/Ar cooling properties)



SN: profiles at targets



Lower target temperature with **wide divertor** at both targets

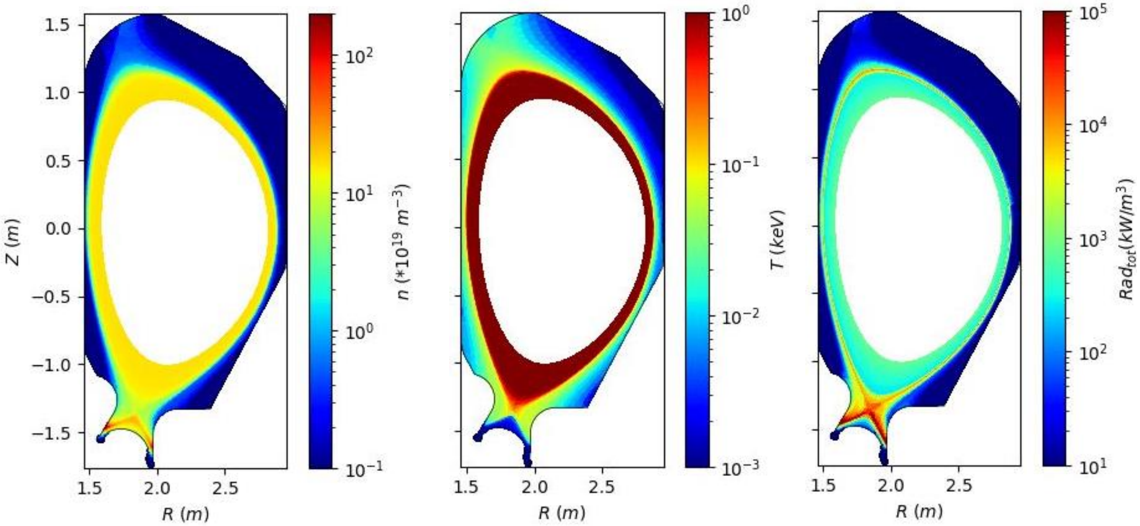
Deep detached conditions achieved only with wide divertor

Partially detached condition with standard divertor

Lower peak heat flux at inner target with standard divertor **(drifts can change this result)**

Standard divertor - SN

Neon seeding

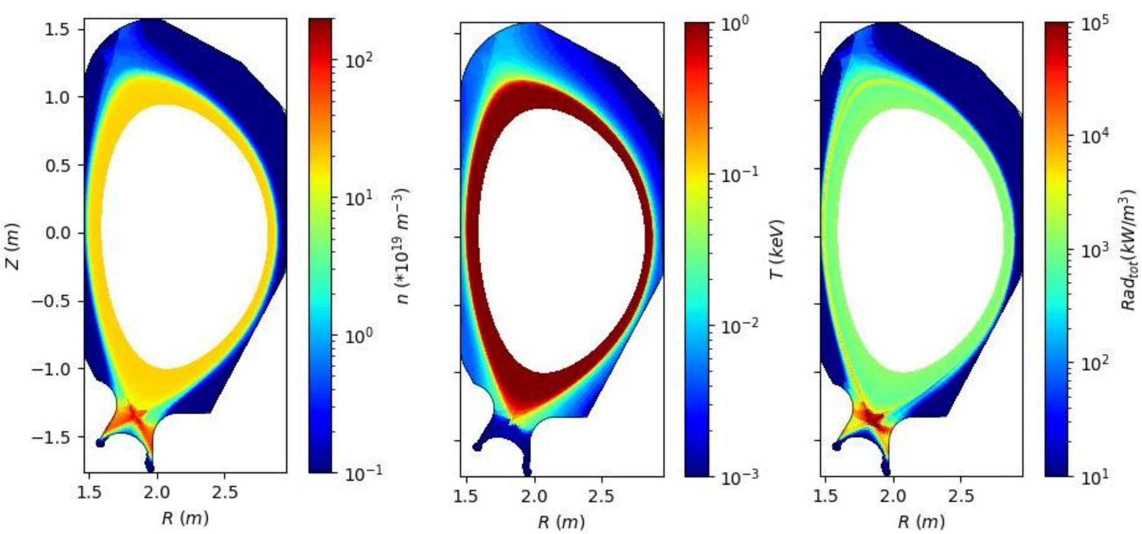


$\langle Z_{eff}\rangle_{sep}=4.8$
$P_{rad,tot}=22$ MW
$P_{SOL}=20$ MW
$C_{Ne}=4.9\%$

Radiation is concentrated on divertor legs

Longer legs provide larger radiative volume

Argon seeding

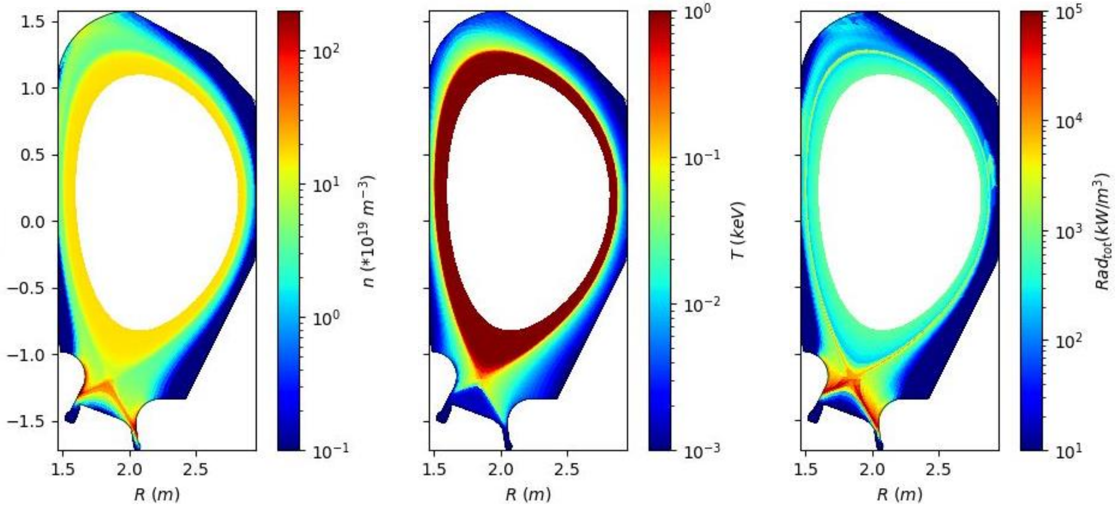


$\langle Z_{eff}\rangle_{sep}=3.6$
$P_{rad,tot}=27$ MW
$P_{SOL}=19$ MW
$C_{Ar}=1.2\%$

Better result with argon
but more radiation at the x-point

Wide flat divertor - SN

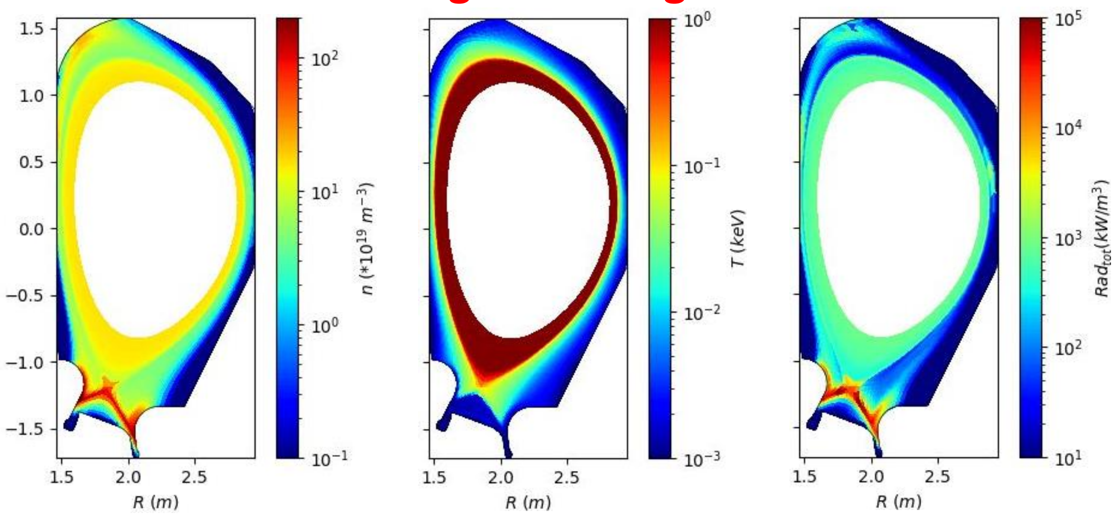
Neon seeding



$\langle Z_{eff} \rangle_{sep}$=3.0
$P_{rad,tot}$=22 MW
P_{SOL}=26 MW
C_{Ne}=2.8%

Radiation is concentrated on divertor legs

Argon seeding

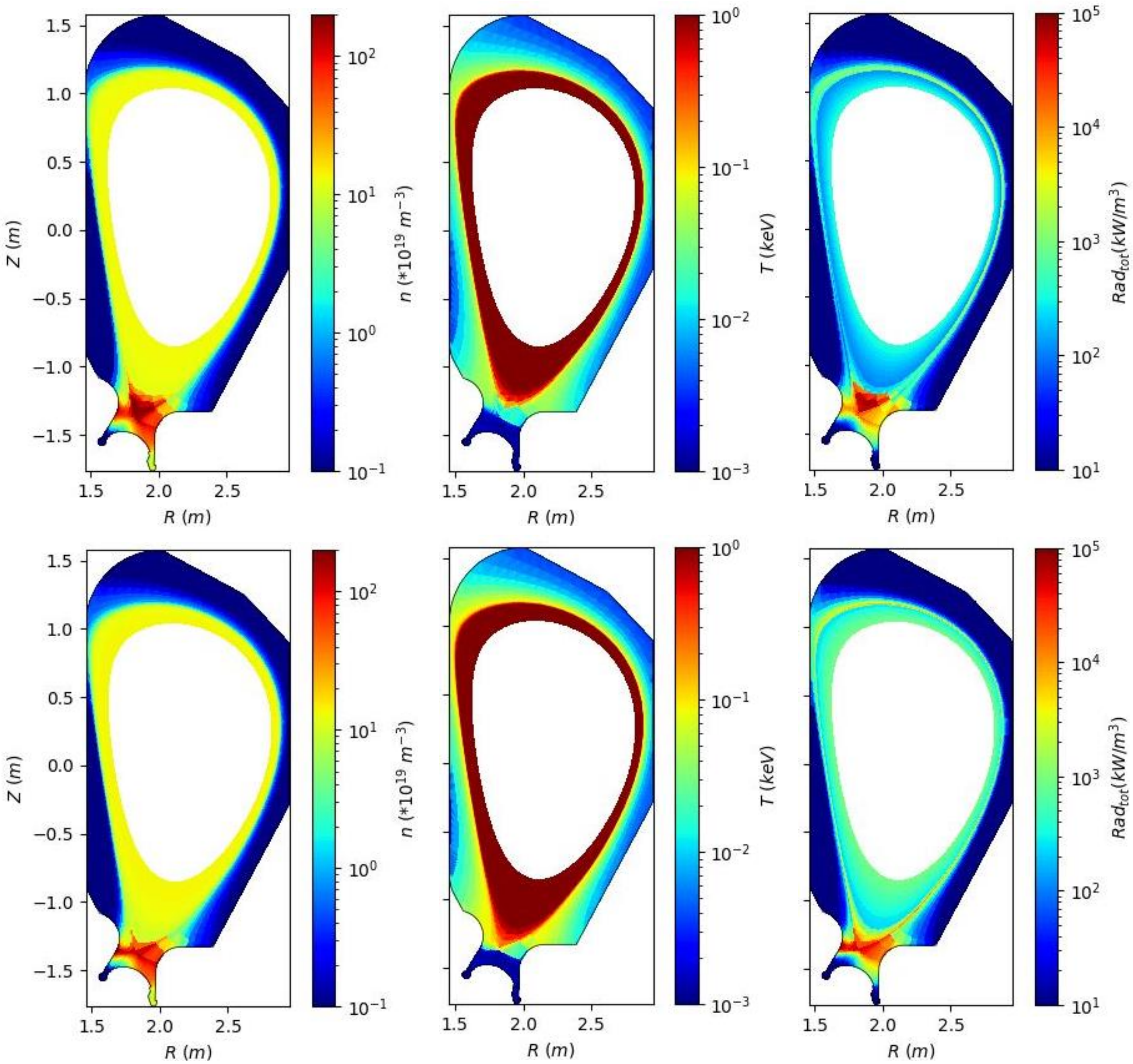


$\langle Z_{eff} \rangle_{sep}$=2.8
$P_{rad,tot}$=23 MW
P_{SOL}=24 MW
C_{Ar}=1.0%

Argon provide better results than neon with similar radiation in the core

Standard divertor – XD with neon

XD configuration easily falls down to X-point radiator



$\langle Z_{eff} \rangle_{sep}$=2.4
$P_{rad,tot}$=28 MW
P_{SOL}=8 MW
C_{Ne}=3.6%

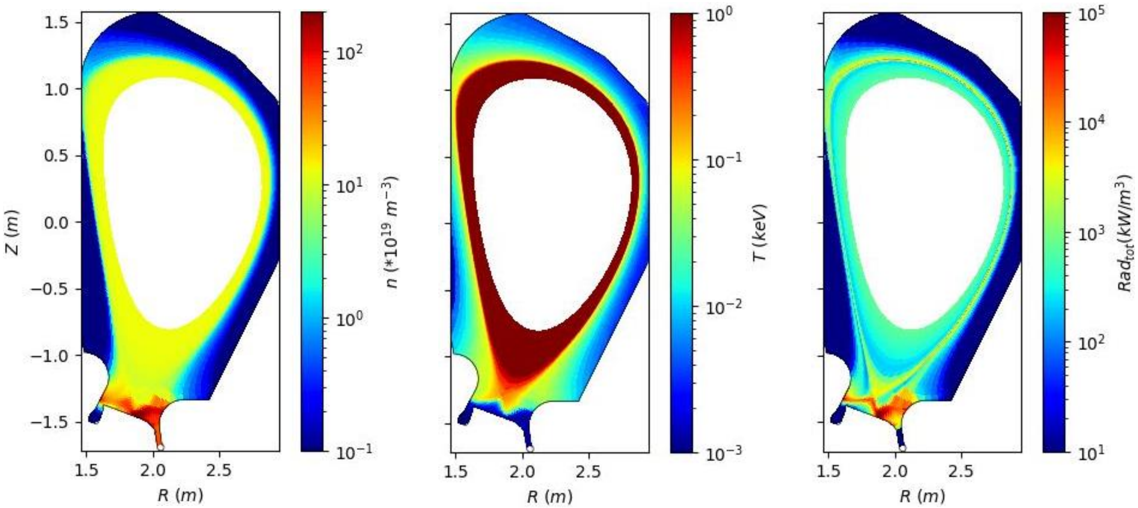
Fast cooling of legs
Radiation localize at the x-point
Most radiation inside separatrix
Unable to sustain H-mode

$\langle Z_{eff} \rangle_{sep}$=4.5
$P_{rad,tot}$=25 MW
P_{SOL}=21 MW
C_{Ne}=7.3%

H-mode condition can be recovered but at high impurity concentration
Can sustain H-mode

Wide flat divertor - XD (short and long leg)

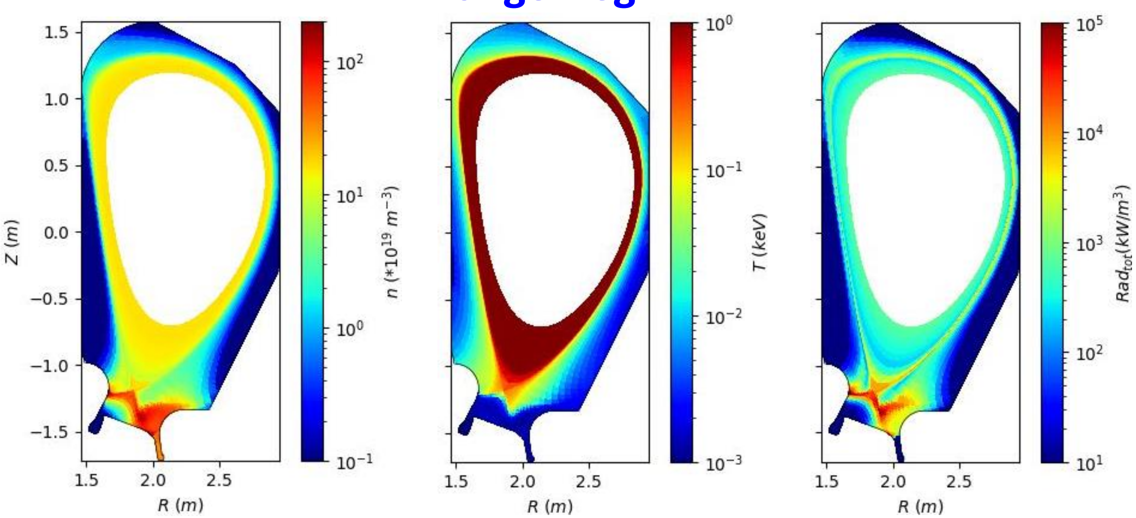
Short leg XD



$\langle Z_{eff}\rangle_{sep}$=3.6
$P_{rad,tot}$=27 MW
P_{SOL}=24 MW
C_{Ne}=4.6%

H-mode operation is possible with a reasonable impurity content

Longer leg XD

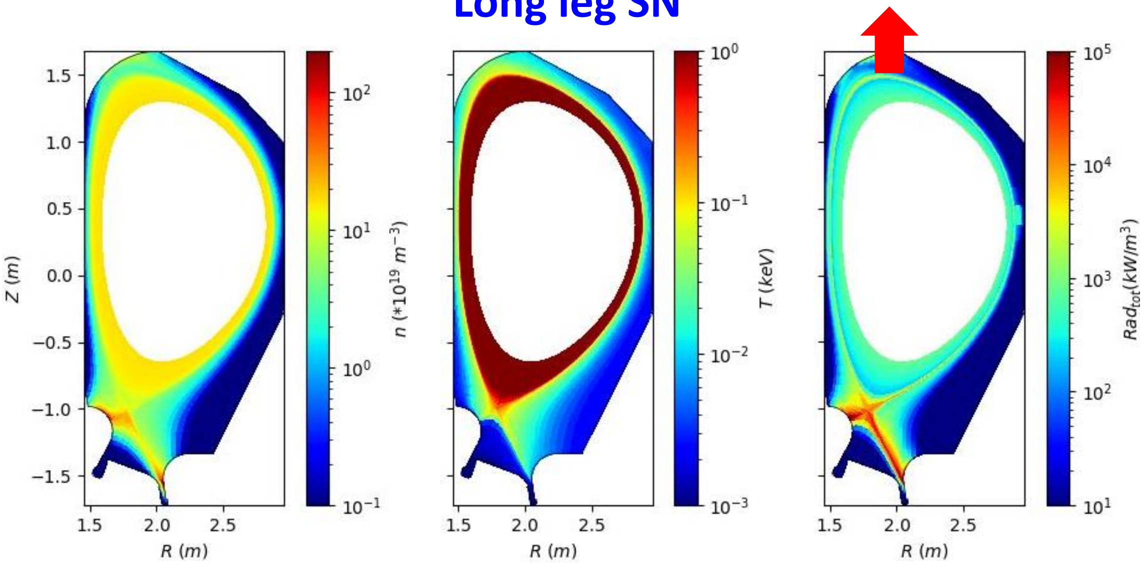


$\langle Z_{eff}\rangle_{sep}$=3.4
$P_{rad,tot}$=25 MW
P_{SOL}=24 MW
C_{Ne}=3.4%

A Longer leg provide better results

Long leg configurations with neon

Long leg SN

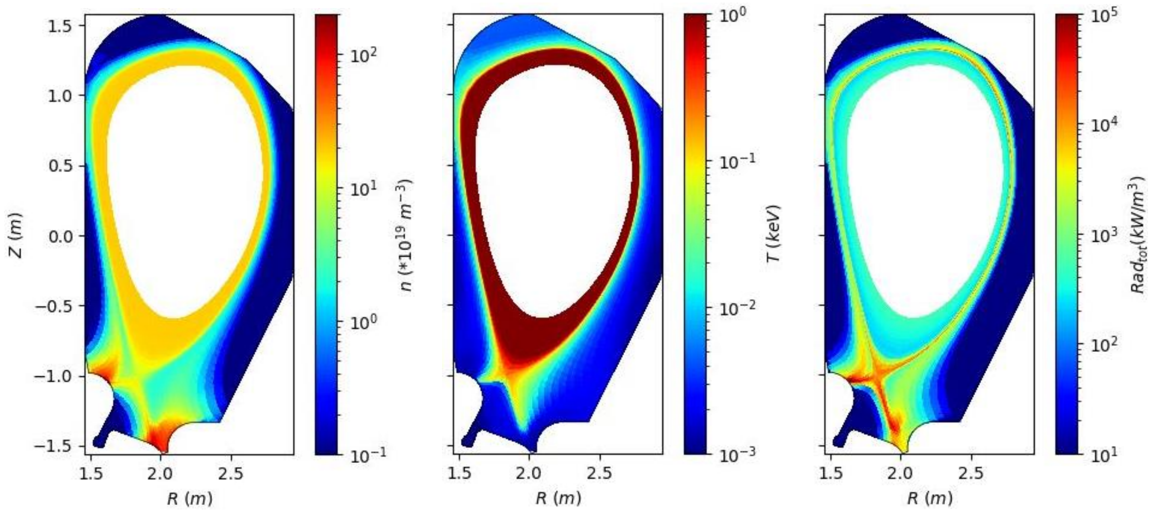


$<Z_{eff}>_{sep}$=3.8
$P_{rad,tot}$=24 MW
P_{SOL}=24 MW
C_{Ne}=4.3%

Long external legs provide a bigger radiative volume reducing request on impurity

But top wall must be move upward

Long leg XD (SXD)



$<Z_{eff}>_{sep}$=2.9
$P_{rad,tot}$=25 MW
P_{SOL}=25 MW
C_{Ne}=1.9%

SXD provides less impurity content in the core thanks to a higher top pedestal density

Comparison of modeling results

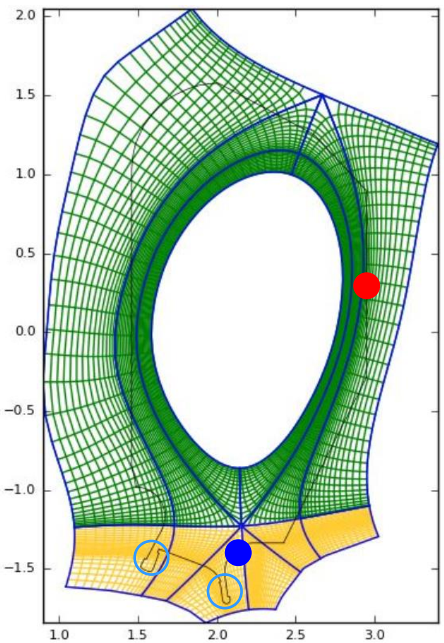
Edge modeling results with the proposed shape (WDF) have been compared to those on a standard medium size divertor (SD) with same SN grazing angles and with a central dome

- **Proposed divertor perform better for SN (pure D, neon/argon seeding) than standard divertor**
- With seeding long external leg configuration allowed by the wide divertor provide similar or better results (SXD)
- **Short external leg XDs are difficult to control to avoid x-point radiation both in SD than in WDF**
- **Long leg XD configurations allowed by the wide divertor does not suffer the X-point radiations behavior and could provide good results**
- **Long leg SN can also provide good results but must be optimized the equilibrium and/or first wall at the top**

Shape	SN/Ne	SN/Ar	LXD/Ne	Long-SN/Ne	SXD/Ne
Standard	**4.8 (19)**	**3.6 (19)**			
WDF	**3.0 (26)**	**2.8 (24)**	**3.4 (24)**	**3.8 (24)**	**2.9 (25)**

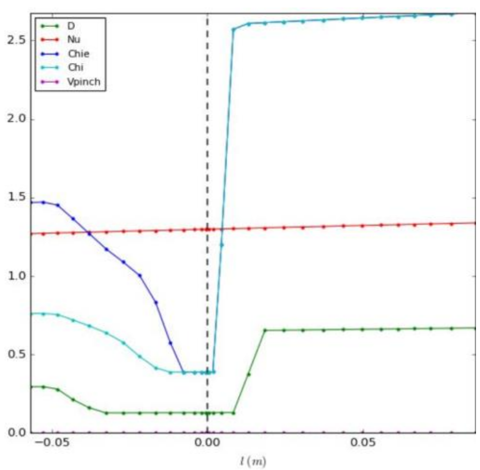
[*] $<Z_{eff}>_{sep}$ (P_{SOL})

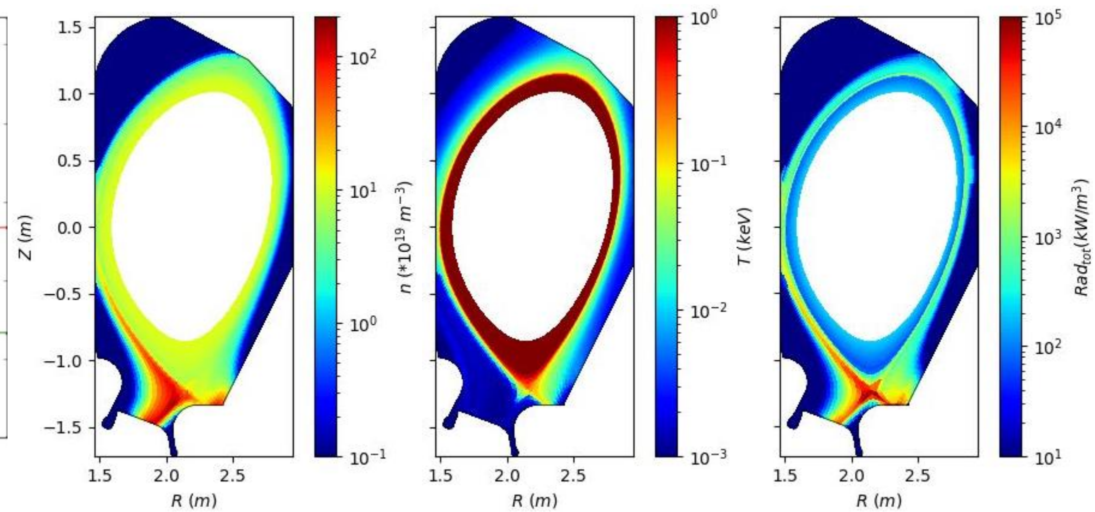
Negative triangularity



Edge modeling has been done also for negative triangularity

- Transport values **have been assumed** in between those for L-mode and H-mode : No ELMs & low impurity ➔ P_{IN}=36 MW
- **Detachment can be achieved easily at the inner strike point** (due to higher edge transport) already at $n_{sep}=7\cdot10^{19}\ m^{-3}$
- Short external leg makes more difficult to achieve detachment at the outer strike point
- Pumping capability is lower than in PT but relatively good in detached conditions (at inner strike point)



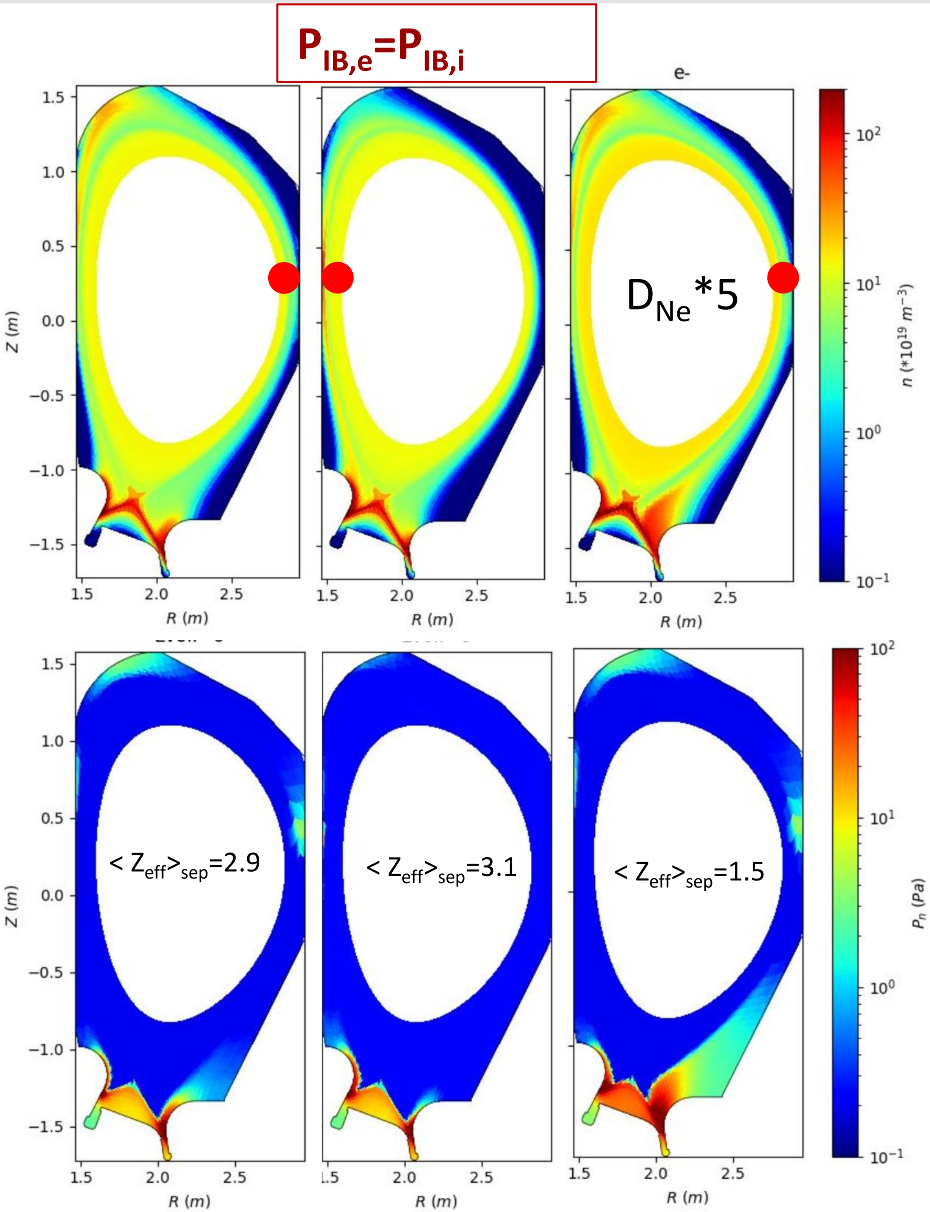


$\langle Z_{eff}\rangle_{sep}$=2.5

$P_{rad,tot}$=28.8 MW

C_{Ne}=1.5%

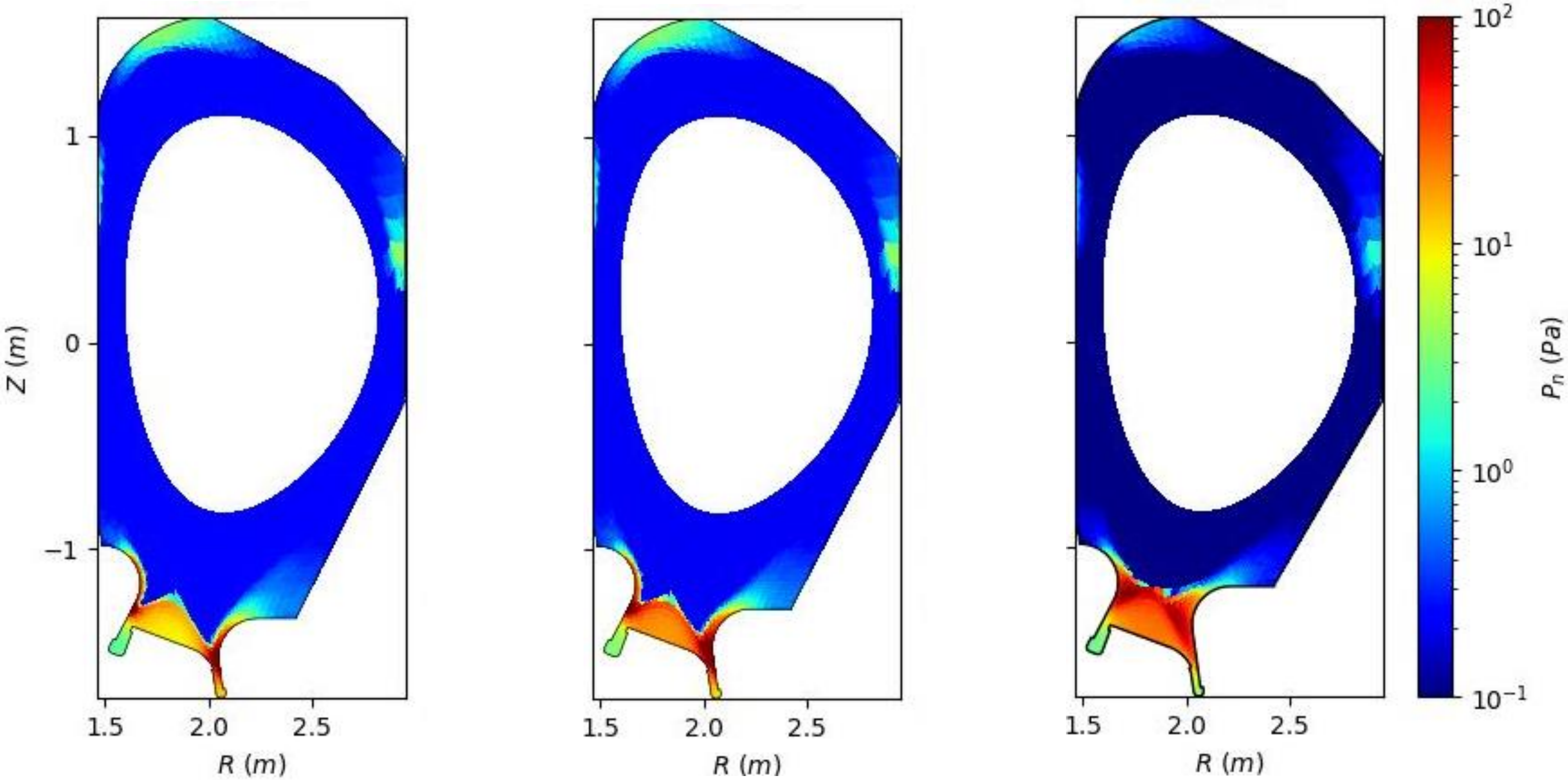
Comparison on transport and puffing position



Tested different gas-puffing locations, equal P_{IB} splitting between electron and ions, higher impurity transport or lower divertor transport

- **Splitting P_{in} equally between ions and electrons does not change to much the final result**
- **Moving gas puffing location to the high field side seems to require a higher $\langle Z_{eff}\rangle_{sep}$ to achieve the same radiation level at the same separatrix density (at OMP) but the difference is well inside uncertainties**
- **Increasing impurity transport will reduce the required impurity content ➔ a better estimation of impurity transport is required**
- **Instead reducing transport in the divertor region does not change significantly the final result (not shown here)**

Effect of external target length



Ref. conf.

+5 cm

+15 cm

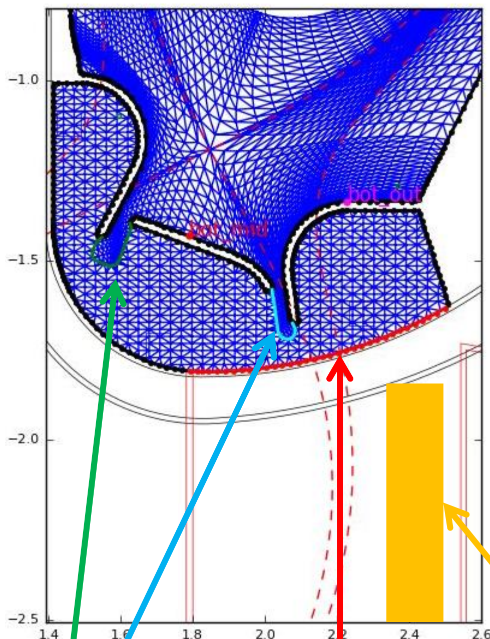
Increasing outer target length will reduce neutrals pressure outside the divertor

But not a clear effect has been seen on exhaust performance (Z_{eff} or C_{imp})

Increasing outer target length will reduce max plasma current for NT configuration

Preliminary assessment of pumping

Sub-divertor EIRENE mesh to compute particle fluxes in a more realistic way



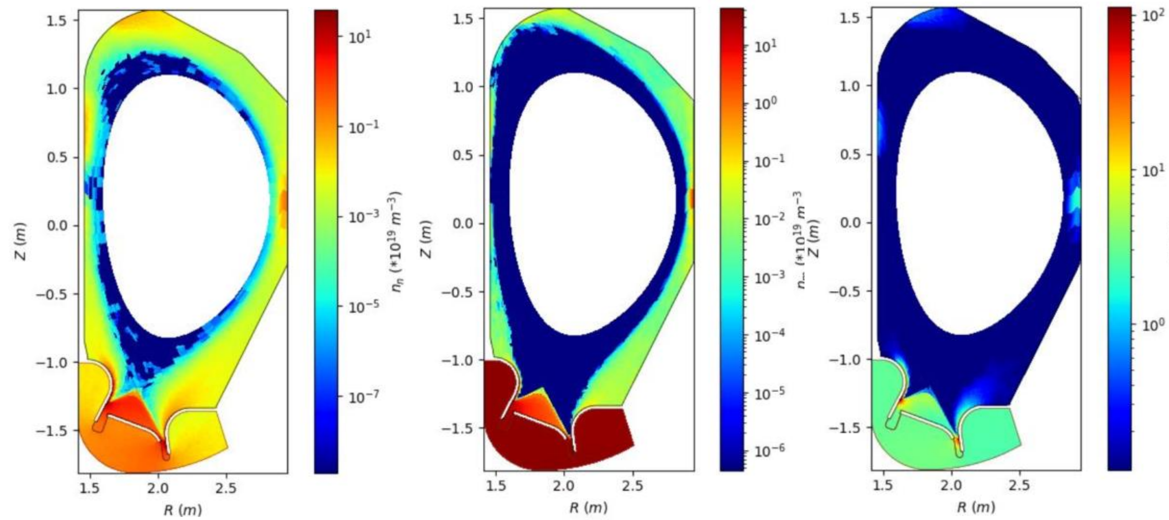
Pumps surface

Partially reflecting surfaces R=0.6

Pumps

A preliminary* assessment of pumping has been done with EIRENE including sub-divertor in modeling and setting pumps entrance a the vertical port entrance.

Atomic and molecular density and pressure



- **D Puffing Γ=5.4·10^{22} D/s**
- **Ne Puffing Γ=0.11·10^{22} Ne/s**
- Few Pa of pressure in the sub-divertor region

* A better assessment will be done by KIT with DIVGAS

Conclusions

- A divertor shape able to accept many magnetic divertor configuration has been studied and optimized by the edge code SOLEDGE2D
- The wide divertor can provide reliable operation for SN and XD configurations in pure deuterium at reduced power and with seeding at full power
- The wide divertor provides better exhaust performance than a standard narrow divertor
- With the designed pumping aperture it provides a high pumping capability for the SN configuration, less for the XD one (and NT)
- Results depend on transport parameters, different values for impurities or at different density can affect final conclusion
- Fine tuning on magnetic configurations (strike point position, separatrix distances) can also affect result

Thanks