EUROfusion

Numerical simulation of neutral gas dynamics in the W7-X sub-divertor

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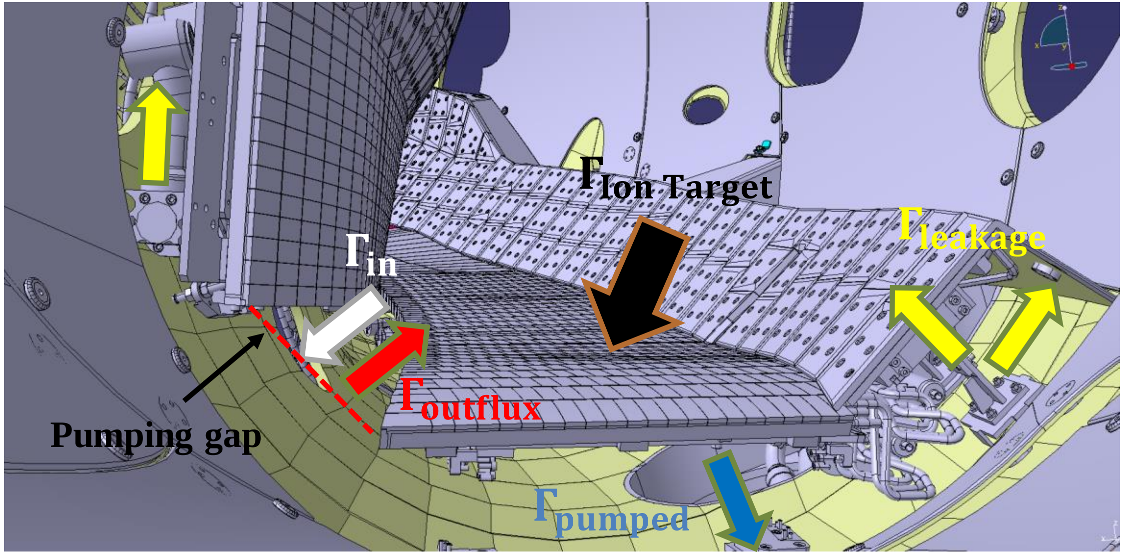
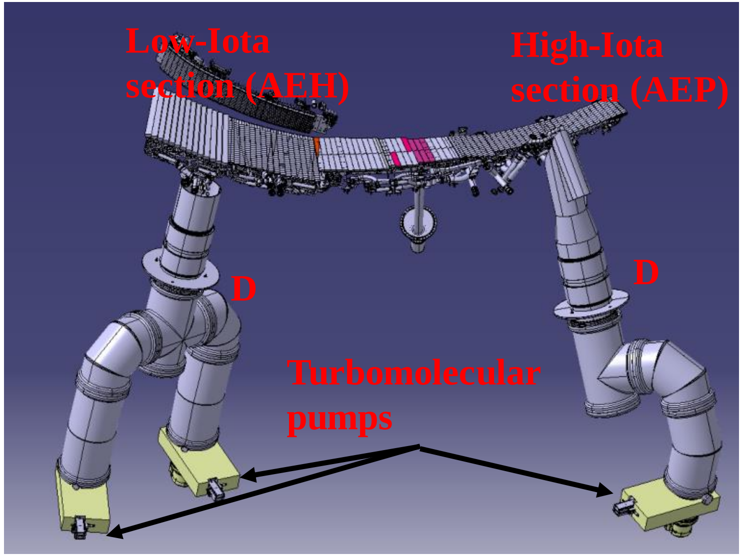
Introduction

- The main objective is that the stellarator concept can meet the requirements of a future fusion reactor by demonstration of high-performance, steady-state operation.
- The improvement of the neutral gas exhaust and the achieved pumping efficiency, which is essential for density control and He exhaust, is the main driver of this analysis.
- It should be demonstrated that the efficient high gas exhaust can be met by optimization of the current setup.
- It is essential to support the design activities as well as the plasma simulations by extended modelling of the neutral gas dynamics in the sub-divertor area.
- The particle based flow analysis has been investigated by using the DIVGAS code. The DIVGAS code has been developed at Karlsruhe Institute of Technology (KIT) and is based on the Direct Simulation Monte Carlo (DSMC) method.
- The gas flow in the sub-divertor volume of a tokamak or a stellarator, may cover a wide range of the Knudsen number starting from near viscous flow conditions close to the interface with the plasma until the free molecular flow (i.e collisionless flow) close to the vacuum pumps.
- The core of the present work consists of the simulation of the 2D and 3D complex sub-divertor region of the W7-X including, additional sub-divertor components.
- This work is being performed for the first time and acts as of a door opener for future design and optimization of stellarator related particle exhaust systems. Without this work, the realistic 3D flow effects, which dominate the flow behavior and hence the pumping efficiency of a stellarator cannot be thoroughly investigated.

W7-X particle exhaust

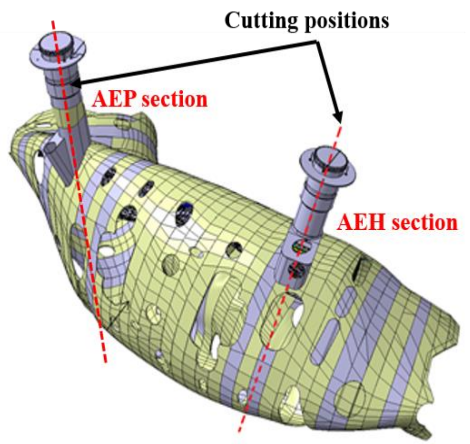


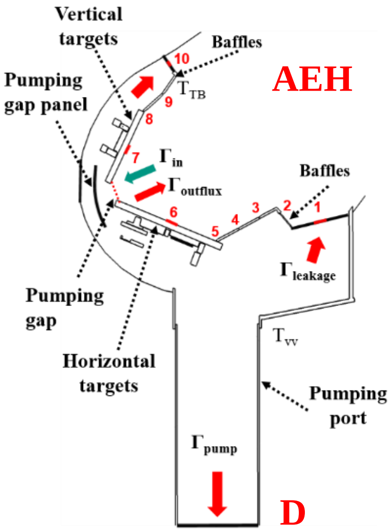


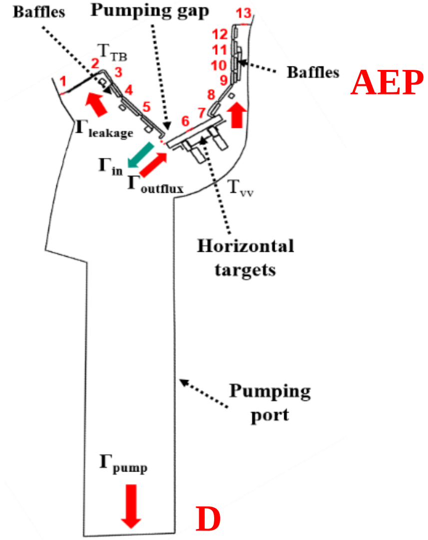
- Gas: H_2, T_{in}=600 K
- $T_{target\ elem.}$= 400 K, T_w=303 K
- Γ_{in} (through pumping gap) = $10^{20} – 10^{22}$ (s^{-1})

- Low-Iota section (2 TMPs): S_{eff}=3.2 m^3/s→ ξ=0.06
- High-Iota section (1 TMP): S_{eff}=1.46 m^3/s → ξ=0.0264

Modelling of 2D Low-Iota and High-Iota sections

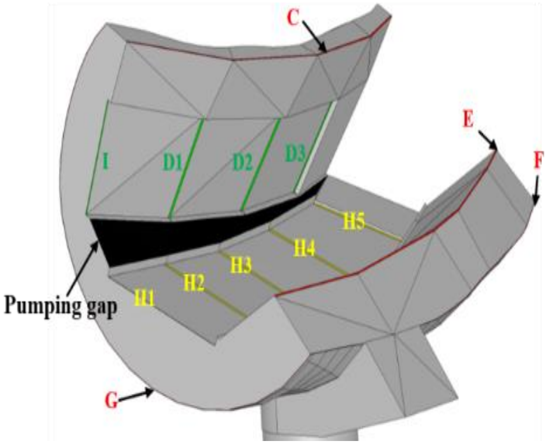


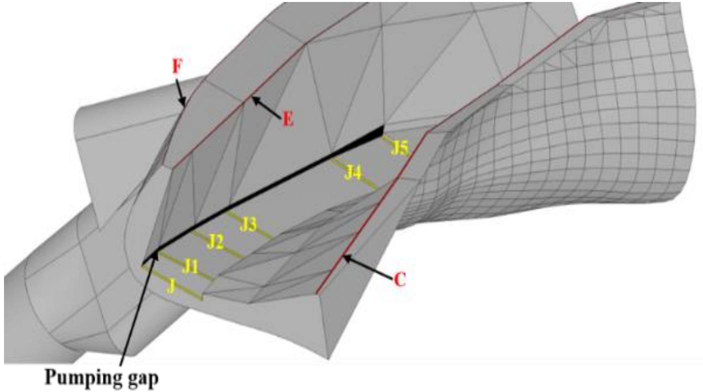




- A 2D representative flow domain has been extracted from corresponding 3D CATIA files. A simplified sub-divertor geometry including internal structures has been considered.
- For the Standard & High-Iota configurations, in total 10 and 13 poloidal leakages through the targets and baffles respectively, have been identified. Their size ranges between 1-15 mm.
- At the pumping surface D, a capture coefficient ξ is applied. The values of ξ range between 0.01-0.5 (i.e pumping intensity).

Modelling of 3D Low-Iota and High-Iota sections





- A 3D representative flow domain has been extracted from corresponding 3D CATIA files. A simplified sub-divertor geometry including internal structures has been considered.
- For the Standard & High-Iota configurations, poloidal and toroidal leakages through the targets and baffles respectively, have been identified.
- At the pumping surface D, a capture coefficient ξ is applied. The values of ξ in the AEH pumping port equal to 0.06, while in the AEP section ξ equals to 0.0264.

Numerical results

- For both Standard and High-Iota configurations, a parametric analysis by varying various flow as well as geometrical parameters is performed.

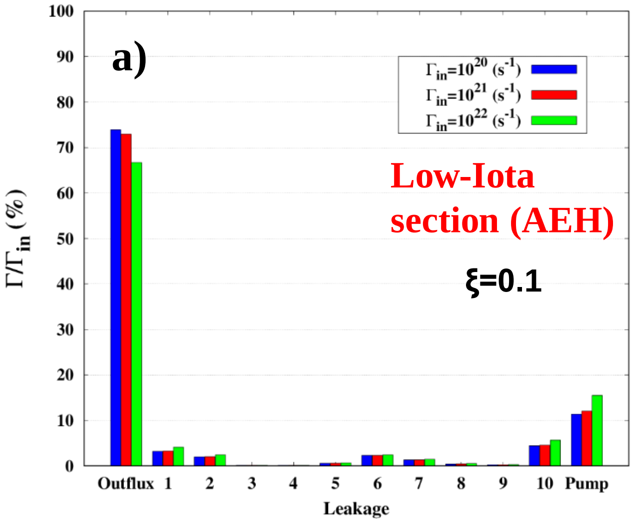
- The main goal is to quantify their influence on the overall particle balance in the sub-divertor area.

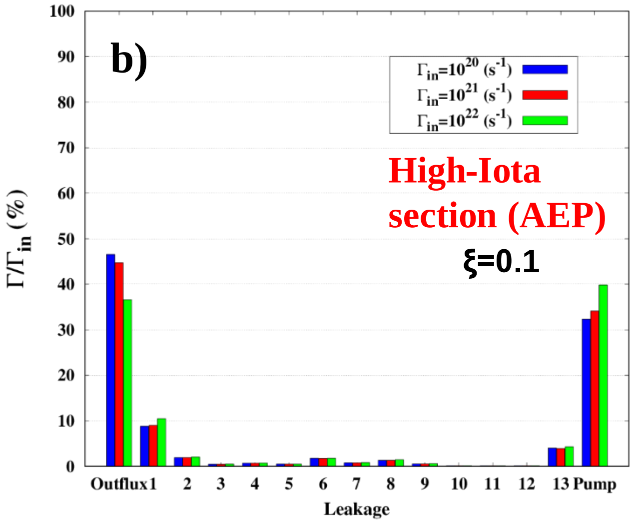
- The main factors, which are considered to have a significant impact on the overall particle balance are:
  i) the incoming neutral particle flux Γ_{in}
  ii) the capture coefficient ξ
  iii) the temperature T_{TB} of the targets and baffles
  iv) the existence of the pumping gap panel
  v) the closure of the poloidal/toroidal leakages

- The present parametric study due to the large amount of cases can only be conducted if a numerical model, which requires reduced computational effort, is used. This is the main rationale for initially adopting the 2D approximation.

- The 3D effects, which describe in a more realistic manner the flow behavior in the W7-X sub-divertor are taken into account by modelling the corresponding 3D models.

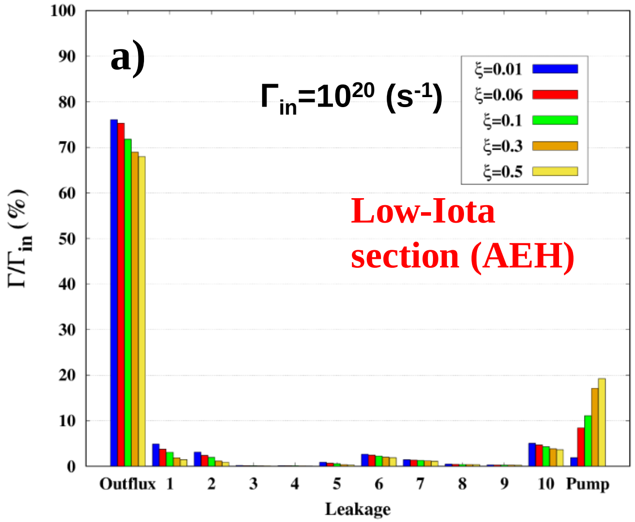
Influence of the incoming neutral particle flux (2D)

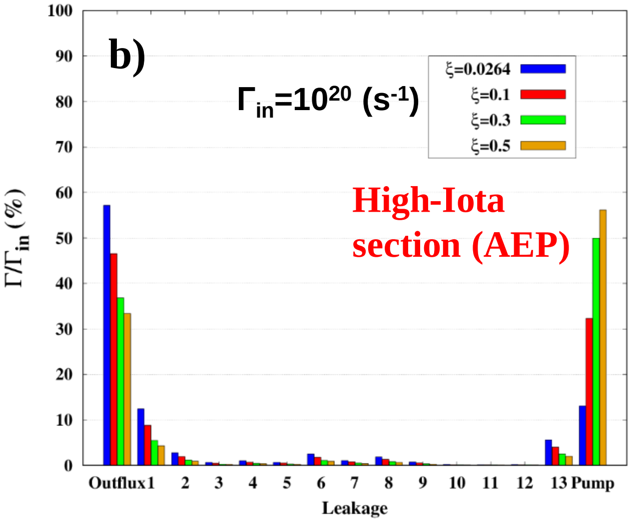




- In both AEH and AEP sections, as Γ_{in} increases the pumped flux increases, while the neutral outflux decreases.
- In the AEH section two orders of magnitude increase in Γ_{in} results in a factor of x1.1 decrease of outflux and a factor of x1.4 increase in the pumped flux.
- For low Γ_{in} the flow regime in the sub-divertor is free molecular and therefore the interaction of particles with the stationary walls, as for instance the pumping gap panel, is more significant compared to the case of higher fluxes, in which the dominant phenomenon is the intermolecular collisions.

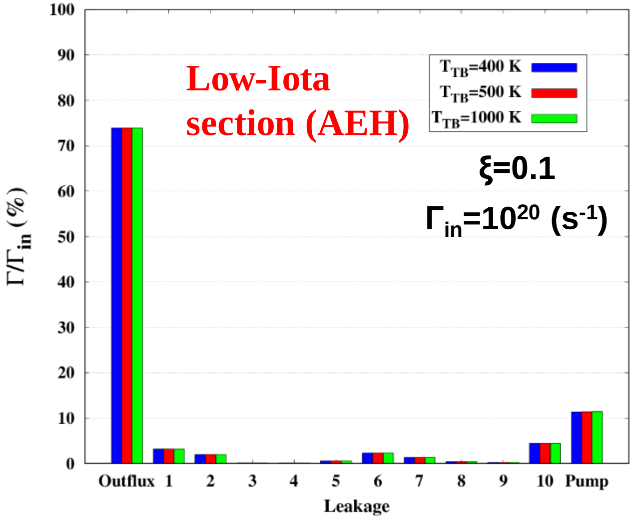
Influence of the capture coefficient (2D)





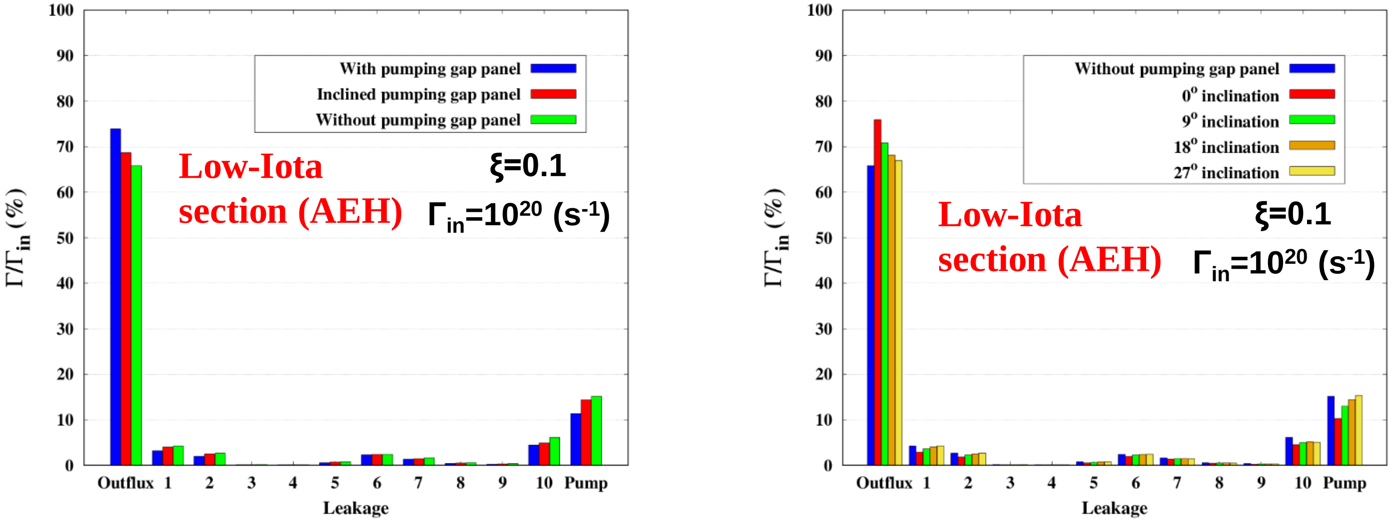
- The neutral particle flux, which goes back to the plasma is always much higher than the corresponding pumped flux.
- As the capture coefficient ξ increases, the neutral pumped flux, denoted as “Pump” increases in a non-linear manner.
- The neutral flux, through the individual leakages as well as the neutral flux, which goes back to the plasma through the pumping gap, denoted as “Outflux”, decreases as ξ increases.

Influence of targets and baffles temperature (2D)



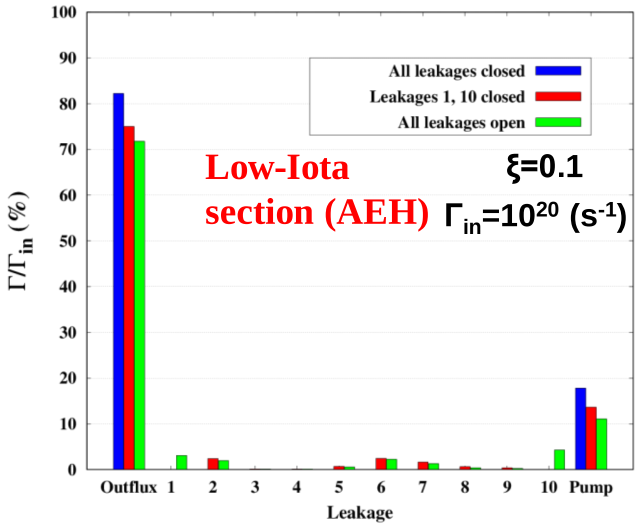
- By increasing the surface temperature of the targets and baffles from 400K to 1000K, there is almost no influence on the particle flux through the individual leakages and openings.
- The main explanation of this effect is based on the behavior of the product of the gas velocity *u* times the local number density *n*, namely *u x n*.

Influence of the pumping gap panel (2D)



- By completely removing the pumping gap panel (assumed as a limit case) a decrease in the outflux by a factor of x1.12 is achieved, while the pumped flux is increased by a factor of x1.33, compared to the case with the pumping gap panel.
- In the case of an inclined pumping gap panel by 9° towards the vacuum vessel (maximum inclination angle to avoid collision with the vacuum vessel), the corresponding decrease in the outflux is by a factor of x1.08, while a factor of x1.26 increase in the pumped flux, is observed.

Influence of the closure of the poloidal leakages (2D)



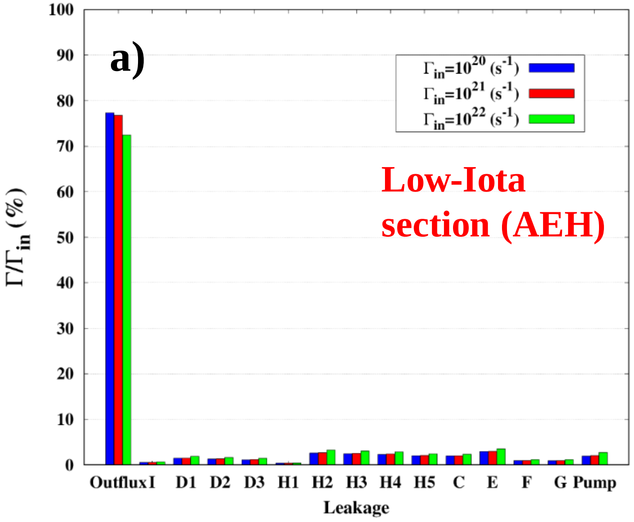
Low-Iota section (AEH)

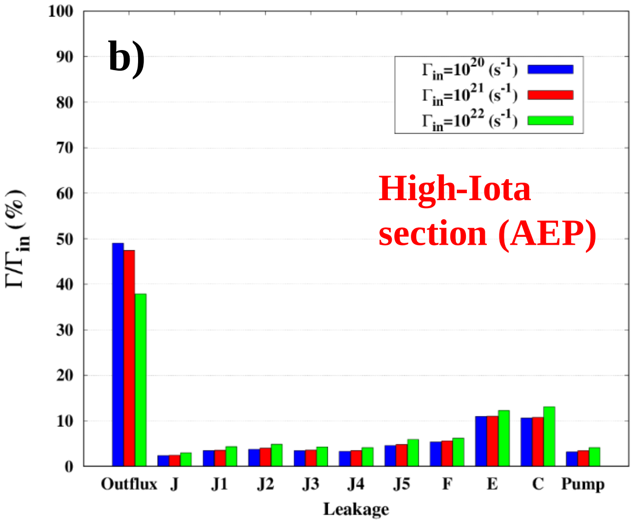
$\xi=0.1$

$\Gamma_{in}=10^{20}$ (s^{-1})

- It is seen, that by closing all the leakages (limit case) an increase in the pumped flux and in the neutral outflux by a factor of x1.6 and x1.1 respectively, is observed.
- In the case that only leakages #1 and #10 are closed then compared with the case with all the leakages open, an increase in the pumped flux and in the neutral outflux by a factor of x1.2 and x1.04 respectively, is observed.
- In general, the closure of the leakages facilitates the increase of the pumped flux and consequently the pumping efficiency of the sub-divertor, but additionally a significant increase in the neutral outflux should be expected (i.e the outflux through the pumping gap back to the plasma).

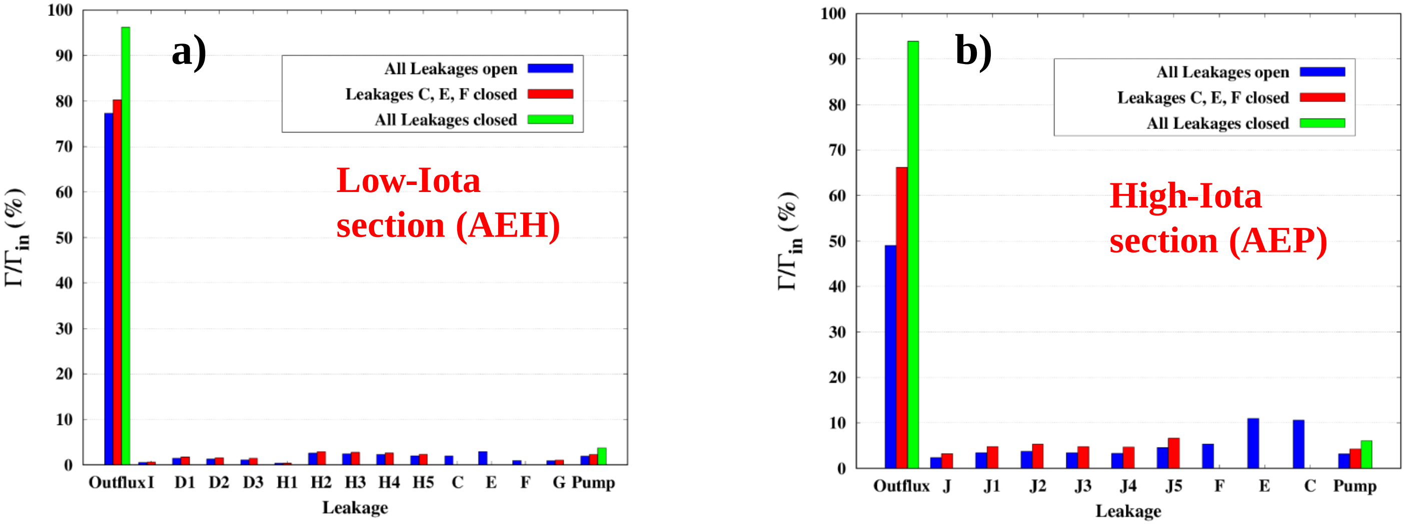
Influence of the incoming neutral particle flux (3D)





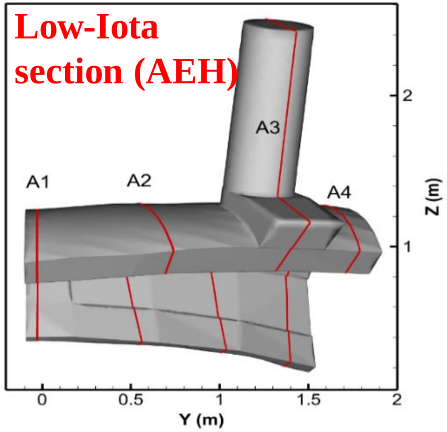
- In both AEH and AEP sections as Γ_{in} increases the pumped flux increases, while the neutral outflux decreases. Moreover, for both sections the pumped flux consists of a small fraction of the incoming flux Γ_{in} compared to the total flux through the leakages.
- From quantitative point of view, for the AEH the outflux and the pumped flux range between 72-77% and 1.9-2.7 % of Γ_{in} respectively, while for AEP the outflux and the pumped flux range between 38-49% and 3-4 % of Γ_{in} respectively.

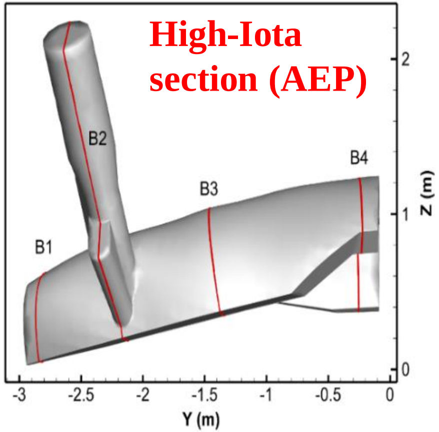
Influence of the closure of the leakages (3D)



- By closing all the leakages (limit case) for AEH an increase in the pumped flux and in the outflux by a factor of x1.9 and x1.2 respectively is observed. For AEP an increase for both pumped flux and outflux by a factor of x1.9, is estimated.
- In the case that only the toroidal leakages C, E and F are closed then compared with the case with all the leakages open, for AEH an increase in the pumped flux and outflux by a factor of x1.2 and x1.03 respectively, is observed.
- Similar values in the 2D simulations have been estimated.

Pressure, velocity streamlines and mean free path





- The estimation of the macroscopic parameters in the sub-divertor area, as for instance the pressure, the velocity streamlines as well as the mean free path λ, for both AEH and AEP sections.
- Four slices in the toroidal direction have been chosen for presenting all the estimated quantities.
- The pressure distribution in the toroidal and poloidal direction for both AEH and AEP section is uniform.
- A non-uniform behavior is observed only in the case of AEH section and in the zone area between pumping gap and pumping gap panel.
- Formation of vortices are observed in both AEH and AEP sections for the case of high incoming neutral flux (i.e 10^{22} H_2/s) due to viscous characteristics of the flow.
- For low incoming neutral flux (i.e 10^{20} H_2/s) and for the case of AEH section, free molecular flow conditions are expected and therefore neutral-neutral collisions could be neglected.
- In all the other cases of incoming neutral flux (i.e 10^{21} and 10^{22} H_2/s) for both AEH and AEP sections, neutral-neutral collisions play a dominant role in the sub-divertor area.

DIVGAS vs Experiments vs ANSYS free molecular

- A direct comparison with corresponding experimental and numerical results has been performed using the experimental data as well as the ANSYS numerical data. Two different plasma discharges of the operational phase OP1.2b are considered, with discharge numbers 20181010.08 and 20180904.31 respectively.

	Discharge 20181010.08		**Discharge 20180904.31**	
	AEH Section	AEP Section	AEH Section	AEP Section
Flow regime	Transition Kn ~O(1)	Free molecular Kn~O(10)	Free molecular Kn~O(10)	Transition Kn~O(1)
Incoming neutral part. flux through the pumping gap Γ_{in} (s^{-1})	3.23×10^{20}	2.66×10^{19}	1.15×10^{20}	2.78×10^{20}
Measured pressure P_{exp} (Pa)	0.014	0.0082	0.0024	0.041
Estimated ANSYS pressure P_{ANSYS} (Pa)	Not valid in this flow regime	0.0041	0.0018	Not valid in this flow regime
Estimated DIVGAS pressure P_{DIVGAS} (Pa)	0.0093	0.0029	0.0033	0.031

- The relative error between experimental measurements and DIVGAS simulations ranges between 24-63%.
- Overall, the present comparison with experiments demonstrates qualitative agreement. In future, this work will be extended to cases with lower Knudsen numbers (i.e higher incoming neutral fluxes), in which the neutral-neutral collisions dominate the flow behavior and aim to a quantitative comparison with corresponding experimental measurements.

Summary and Conclusions

- The present work presents a 2D and 3D modelling of the neutral gas flow in the sub-divertor region of the W7-X using the DIVGAS code.
- The main objective of this study is to investigate the dynamics of neutral particles in the sub-divertor region including the effects due to geometry and toroidal and poloidal leakages on the achieved pumping efficiency.
- A sensitivity analysis has been performed for the effect of various geometrical and flow parameters on the pumping performance, under different plasma scenarios.
- A large fraction of incoming neutral particle flux i.e. > 70% on the Low-Iota (AEH port) side and > 40% for the High-Iota (AEP port) side is leaked back to the main divertor region, higher incoming neutral fluxes facilitate the increase of the pumped flux as well as the decrease of the outflux.
- Small fraction ~3-4% of the incoming neutral flux is pumped via the turbo-molecular pumps installed in the AEH and AEP ports.
- The closure of the toroidal leakages facilitates the increase of the pumped flux as well as the neutral outflux towards the plasma.
- A comparison with available experimental measurements of the neutral pressure in the sub-divertor has been performed for Standard and High-Iota plasma discharges. The DIVGAS simulations predict qualitatively the experimental data with relative deviation between 25 and 63%.
- For low incoming neutral fluxes and for the case of AEH section, free molecular flow conditions are estimated. For higher incoming neutral fluxes and for both AEH and AEP sections neutral-neutral collisions play a dominant role in the sub-divertor area and in the flow establishment.

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