EUROfusion

Plasma exhaust and vacuum pumping on ITER & other devices

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Karlsruhe Institute of Technology

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Outline

- Introduction – ITER Fuel cycle
- Exhaust parameters – Limits in the pumped fluxes
- DIVGAS and objectives
  - Validation of DIVGAS with JET experiments
  - Modelling of ITER, AUG, JT60-SA, DTT sub-divertors
- Integrated DEMO divertor modelling
  - Influence of dome height
  - Influence of inter-cassette gaps
  - Influence of divertor configuration
  - Influence of pumping port location
  - Influence of divertor plasma conditions
- Conclusions – Lessons lernt

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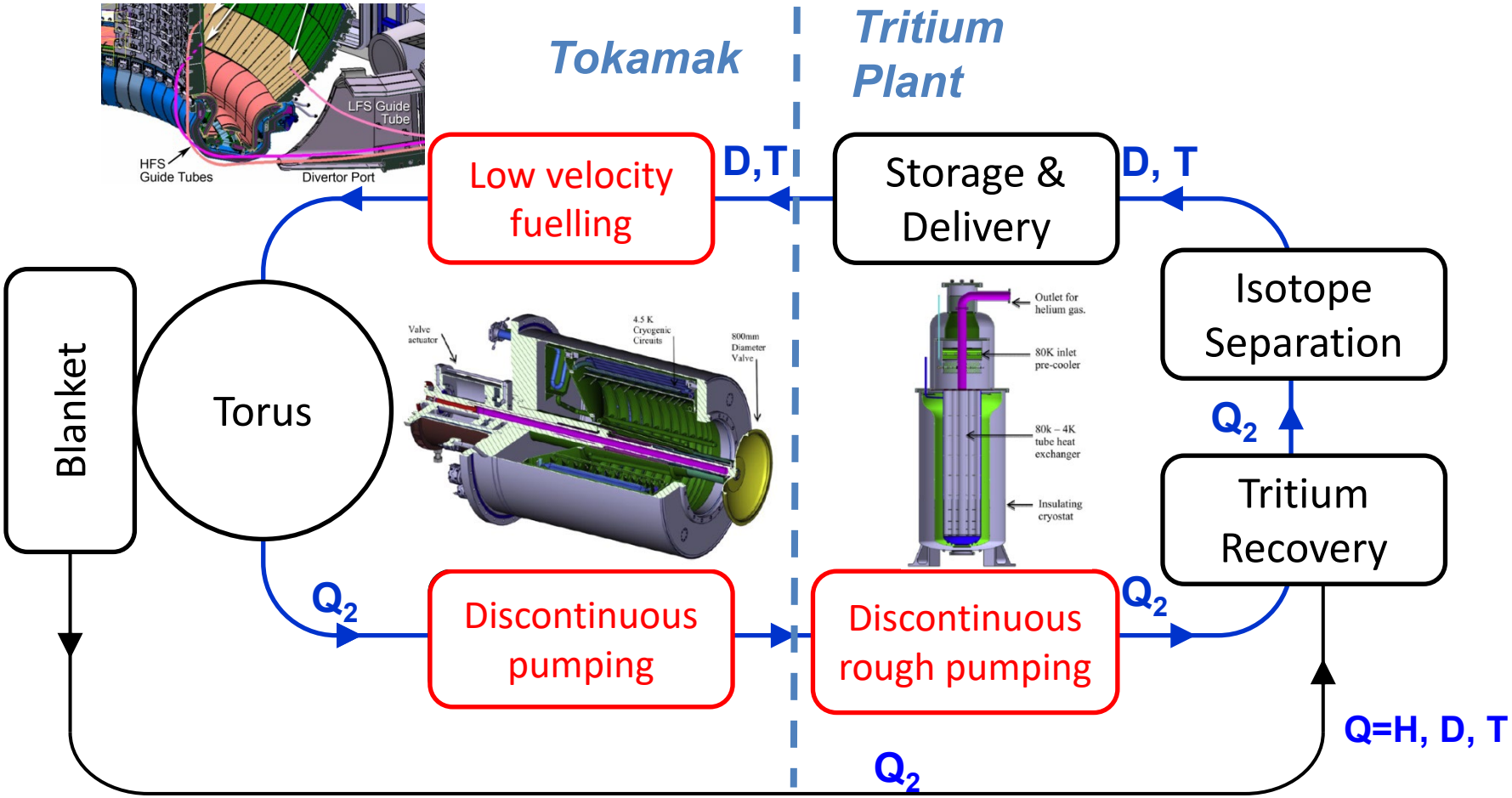
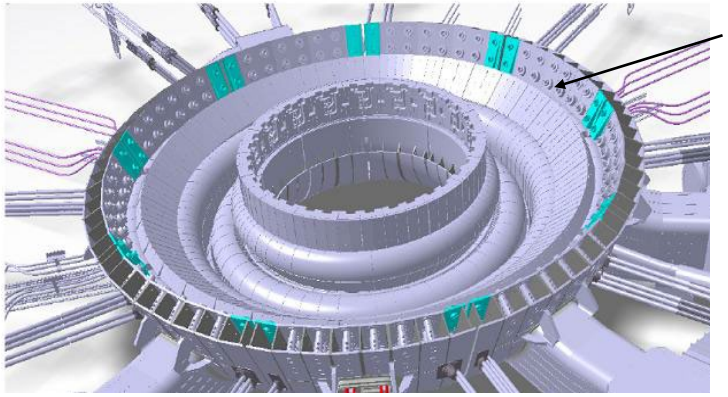
The fuel cycle for ITER

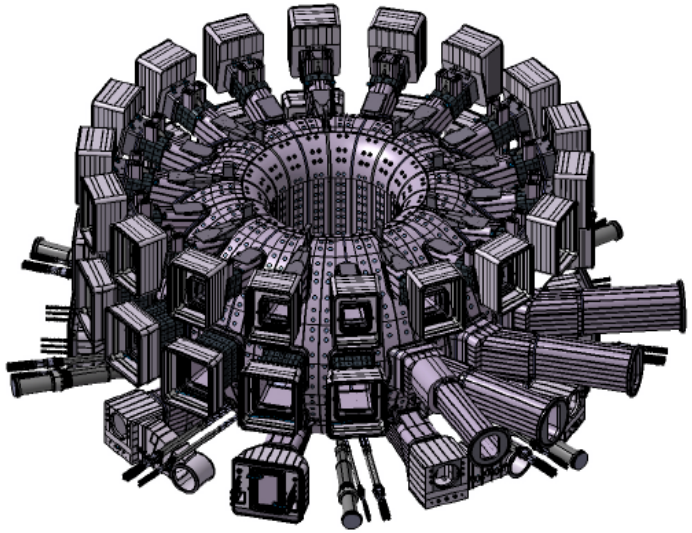


- Discontinuously working pumps increase overall tritium inventory, cryogenic pumps require complex operation.
- Full throughput has to be processed in the tritium plant → huge facility.

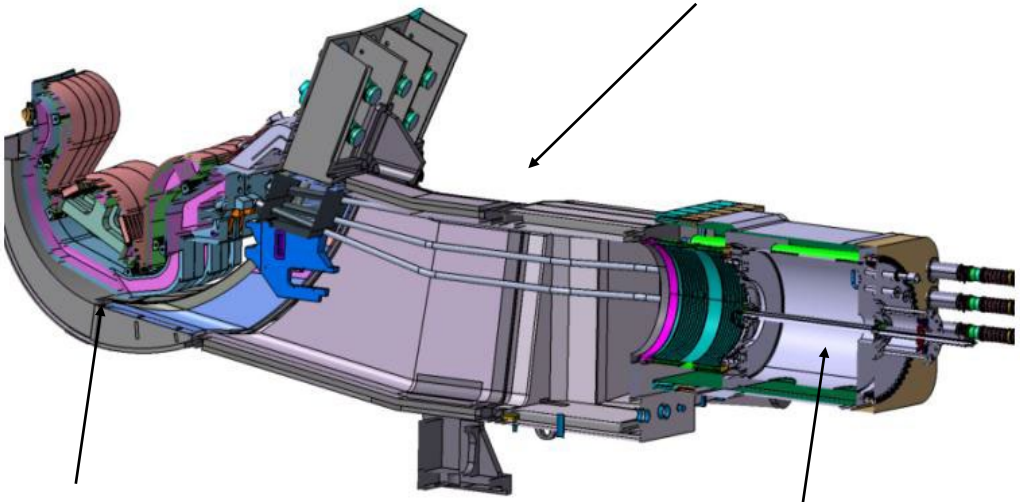
The ITER lower port region: 6 pumps



Ring with 54 divertor cassettes



~ Rectangular pumping channel



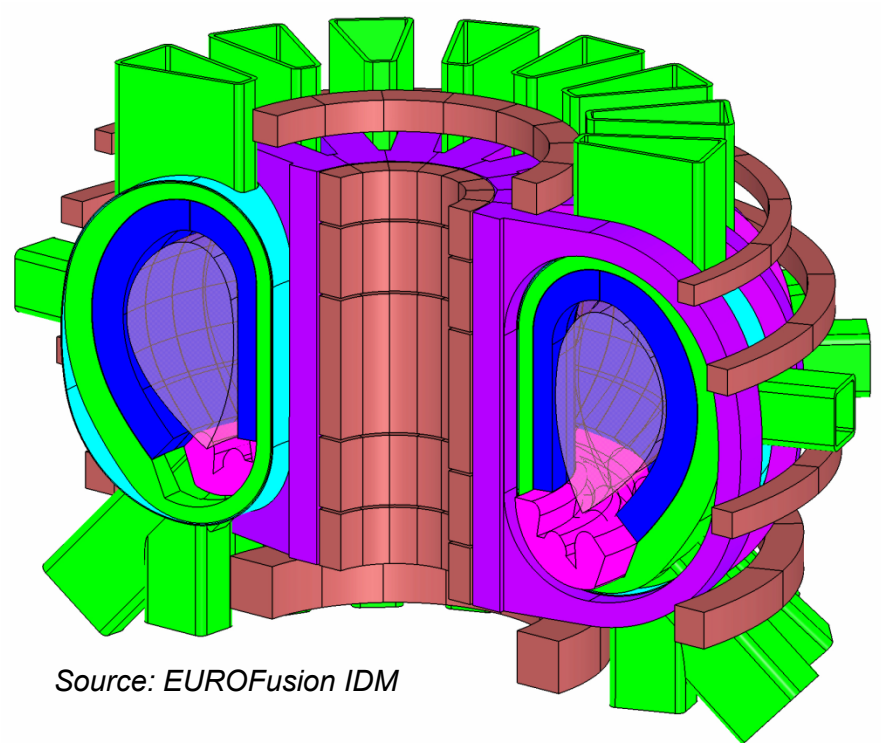
1 Divertor cassette

Cryopump

Laminar.....Transitional……..…Free molecular

Kn~0.01 Kn~500

Towards a power plant



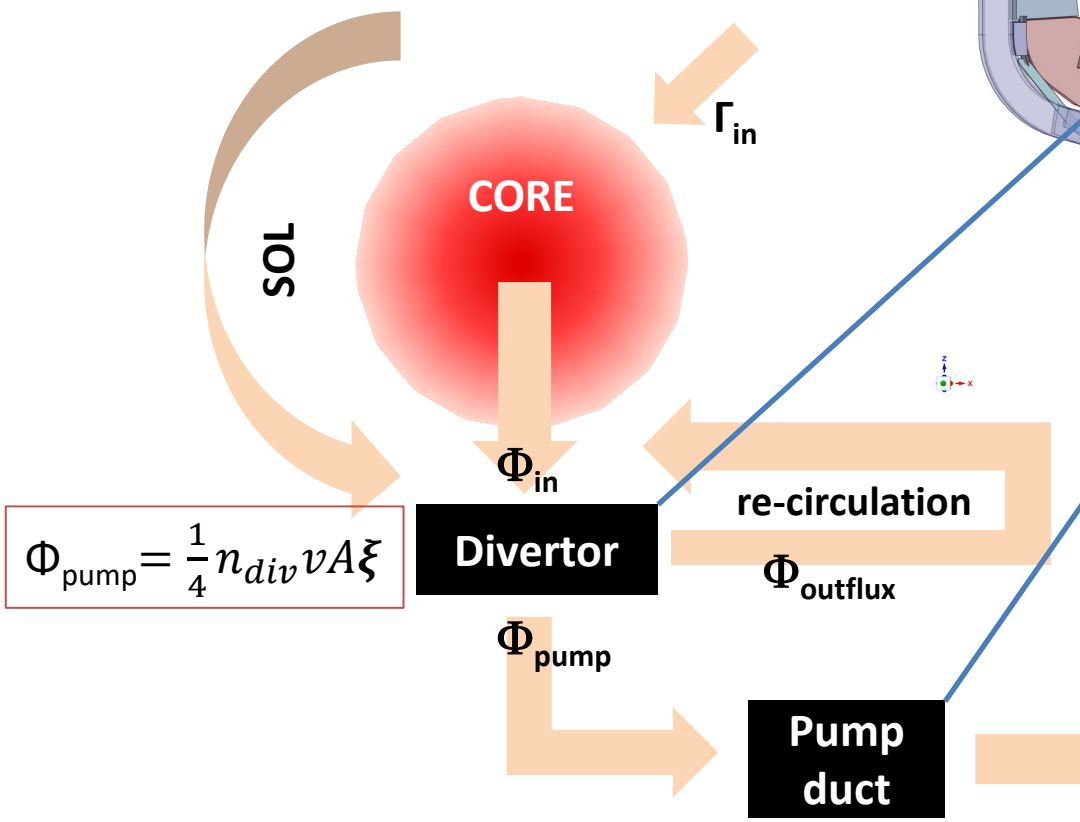
Source: EUROFusion IDM

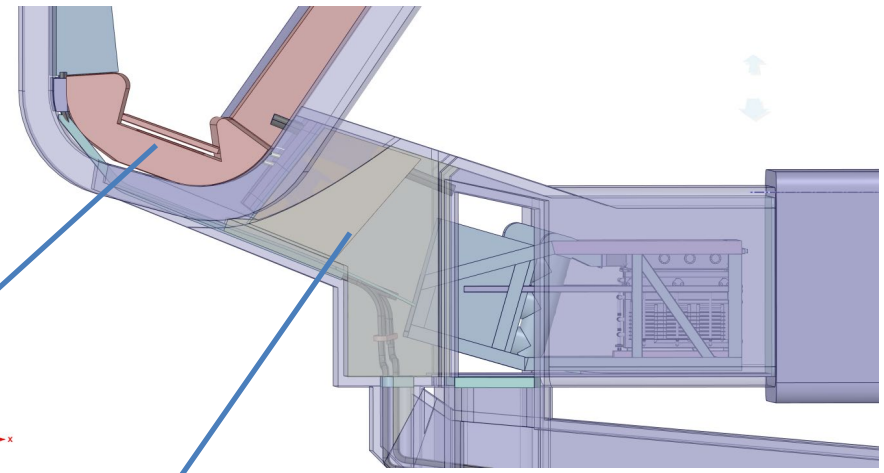
- For DEMO, the baseline design includes an ITER-type divertor, but alternative divertor designs are being explored.
- DEMO scenarios which would define important divertor parameters are not fixed yet (heat load, particle fluxes etc).
- Up-scaling of ITER cryopump technology is critical for DEMO → Excessive tritium inventory in the whole pumping system.

- Control of gas throughput towards the pumps → Affects plasma and divertor performance (pumping system as plasma actuator).
- Description of the gas flow in divertor and vacuum systems → Challenging task, flow covers a wide range of Knudsen number.
- For DEMO, a reliable tool, which can predict overall quantities, the neutral recirculation and improve the exhaust pumping efficiency, is required.

Translation towards exhaust parameters

- At which pumping speed can the machine gas throughput be pumped?
- Competition against recycling and conductance losses





$$\Phi_{pump} = \frac{1}{4} n_{div} v A \xi$$

Throughput = pressure x pumping speed

Clear limits exist for pumped fluxes

Flux conservation translates ξ (PFR) into c (pump)

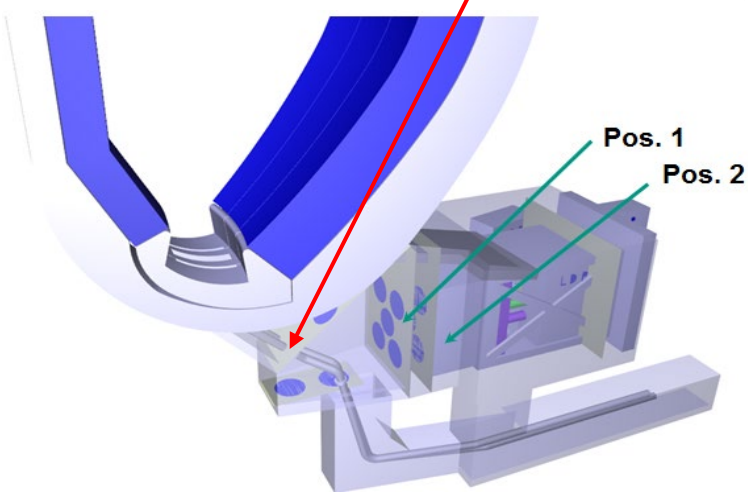
$$\Phi_{\text{pump}} = \frac{1}{4} n_{DIV} v_{DIV} A_{DIV} \cdot \xi = \frac{1}{4} n_{PUMP} v_{PUMP} A_{PUMP} \cdot c$$

Black hole surface related pumping speed (finite)

Inlet surface of the pump

Capture coefficient at the pump inlet, defines pump technology and requirement at the location of the pump

Now: What does the ξ tell us?
→ The number of ports



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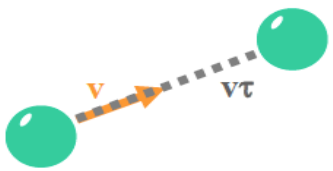
DIVertor GAs Simulator

Geometry
- Extraction of relevant geometry from CAD files
- Definition of interfaces between plasma and neutrals
- Plasma simulations (SOLPS, EDGE2D-EIRENE etc)
- Extraction of boundary conditions (P, T, part. fluxes)

Simulation
- Set-up of the model (2D/3D, single gas, gas mixture)
- Mesh generation
- Pump integration (i.e as a capture coefficient)
- Collisions are included
- Diffuse-specular gas-surface interaction

Post-Processing
- Evaluation of the results
- Comparison with experiments



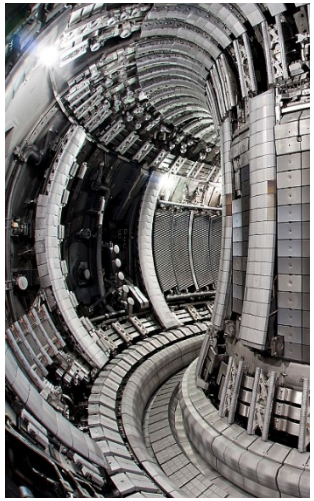
Ludwig Boltzmann
1872 Boltzmann equation

- DIVGAS is based on the deterministic (Discrete Velocity Method) and stochastic (Direct Simulation Monte Carlo) numerical methods.
- The solution of the Boltzmann equation is reproduced.
- Conservation of momentum and energy.
- Correct estimation of transport coefficients.

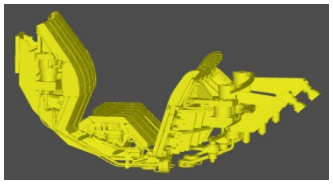
Objective of DIVGAS

- **The main objective of the DIVGAS (Divertor Gas Simulator) code is to develop a multi-machine platform for divertor gas flows**

EFDA JET

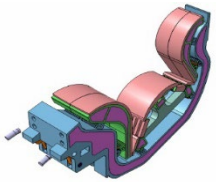


IPP Max-Planck-Institut für Plasmaphysik

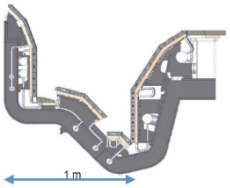


ASDEX Upgrade

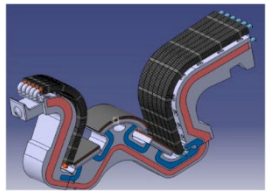
iter



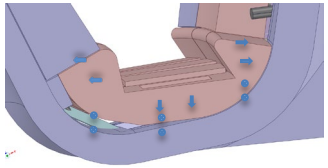
JT-60SA Advanced Superconducting Tokamak BA-Satellite Tokamak Program



DTT

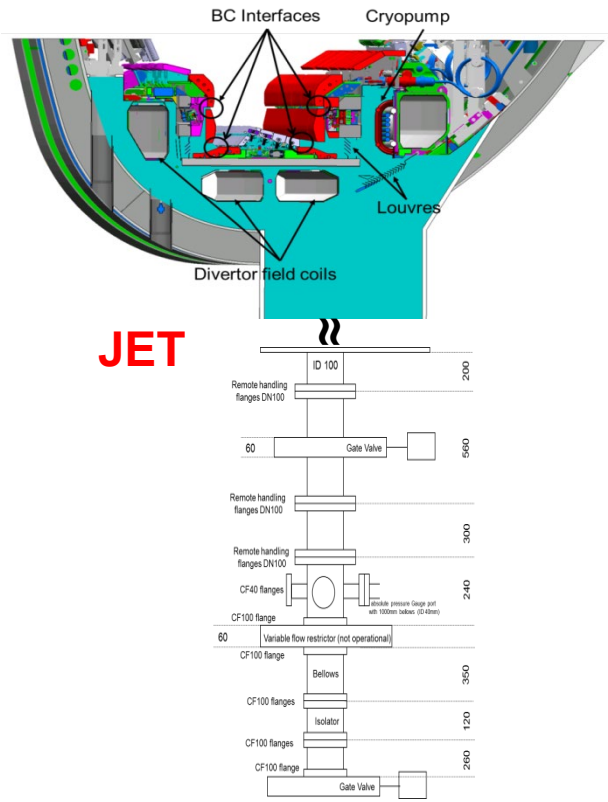


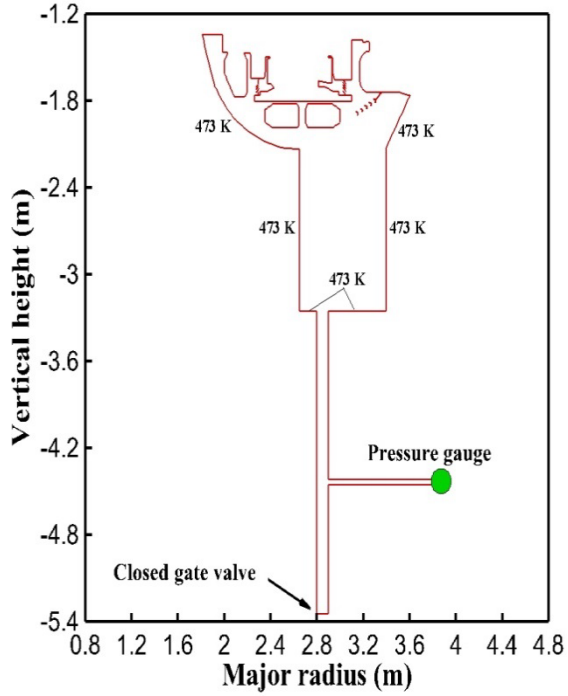
DEMO

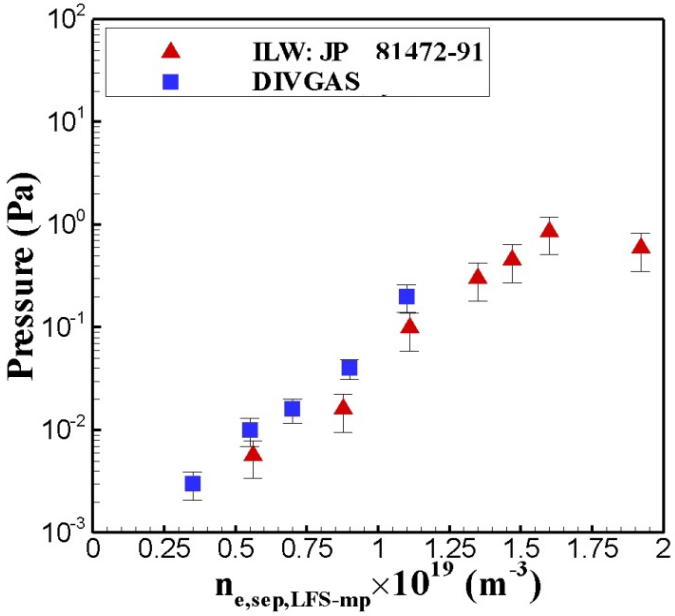


- Validate the code with experimental results in JET and AUG.
- Benchmark the code with the extensive ITER divertor database.
- Apply the code for the design of particle exhaust in fusion devices.

Validation of DIVGAS with JET experiments





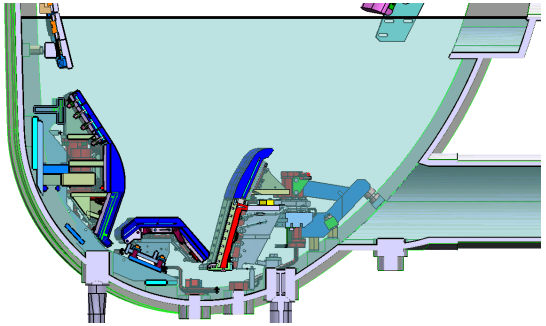


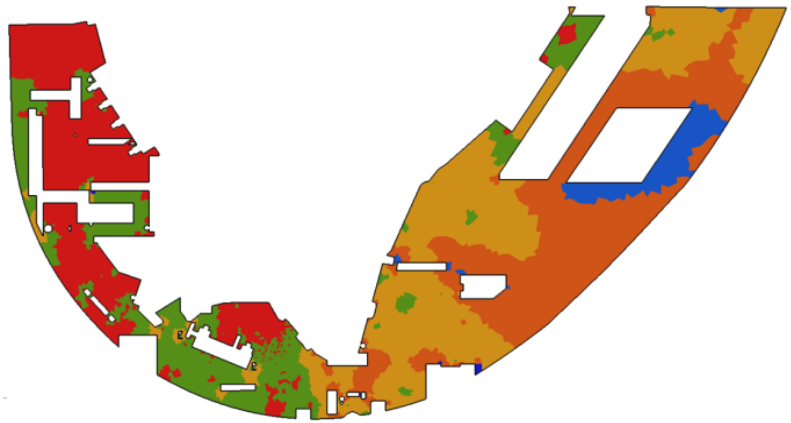
- A 2D-cut of the 3D CATIA model of JET Octant No. 8 is used.
- D_2+D gas mixture flow is assumed, with diffuse gas-surface interaction.
- EDGE2D-EIRENE plasma simulations were used to extract DIVGAS boundary conditions.

S. Varoutis et al., FED, **121** (2017).

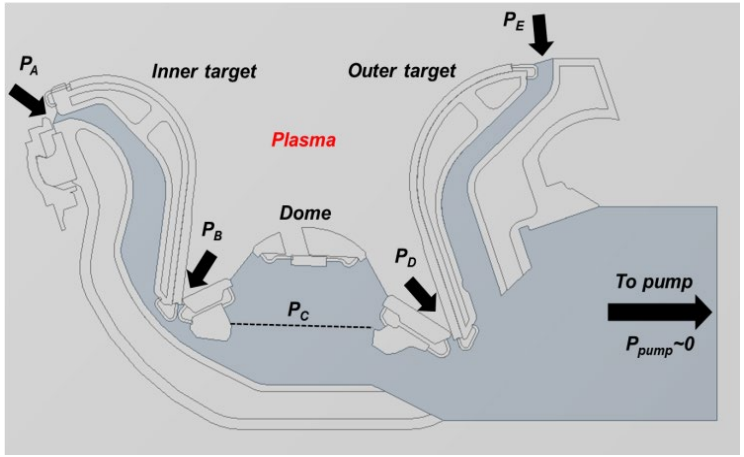
Modelling of AUG and ITER sub-divertors

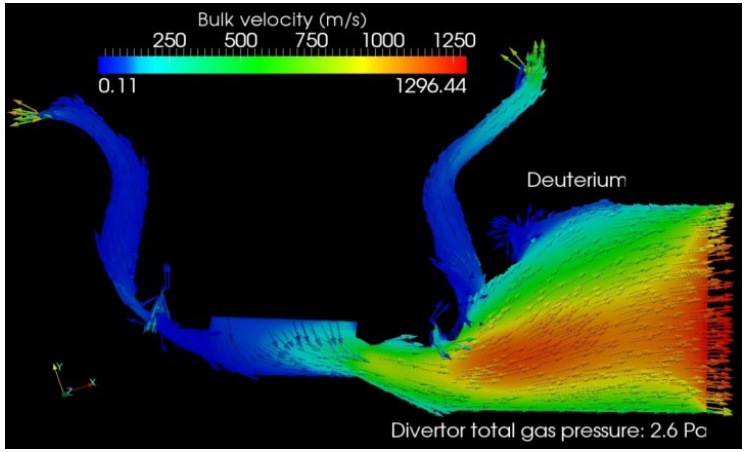
AUG





ITER





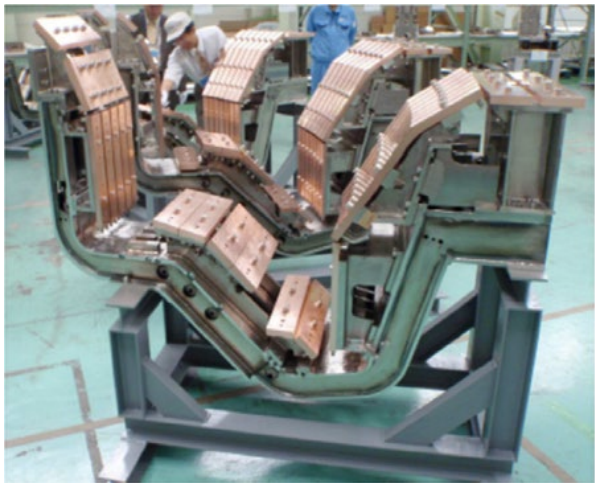
- A strong variation of the gas collisionality in the AUG sub-divertor is observed.
- In ITER the velocity field in the sub-divertor region shows significant neutral recirculation behind the divertor targets.

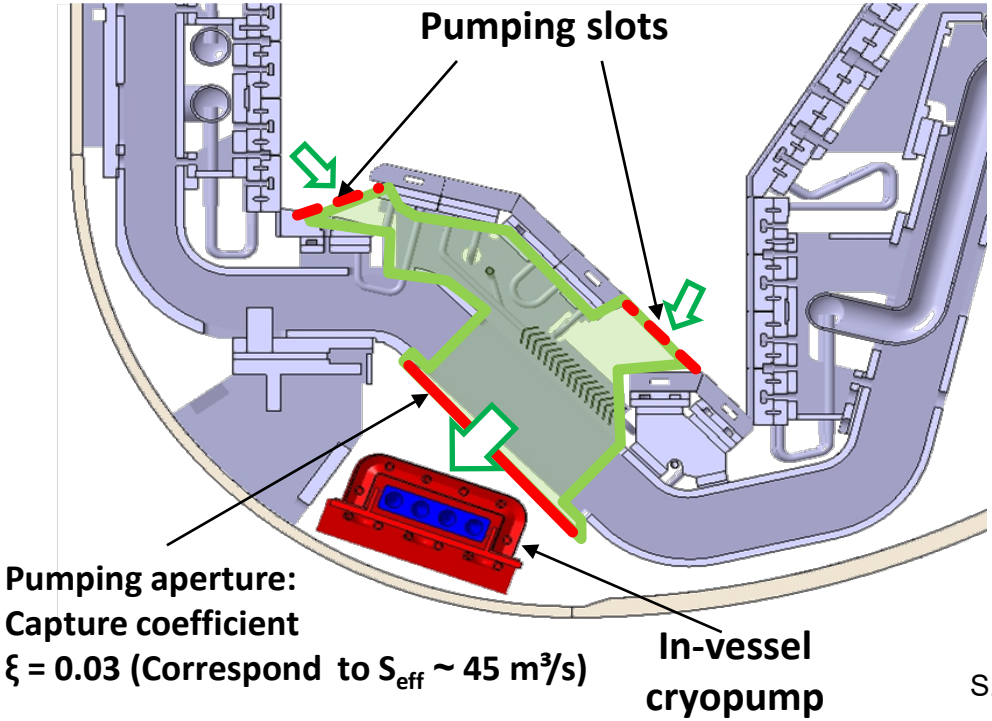
C. Gleason-González et al, FED, **89** (7-8), 1042 (2014).

Modelling of JT-60SA sub-divertor

- The operation regimes for JT-60SA (DEMO relevant high density operation) lead to collisional neutral flows in the sub-divertor.
- Succesfull comparison between DIVGAS & NEUT2D.

JT-60SA



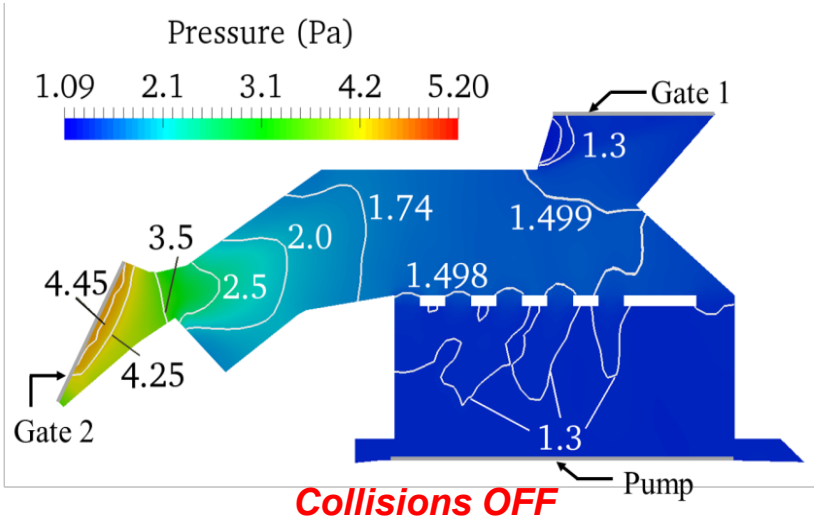


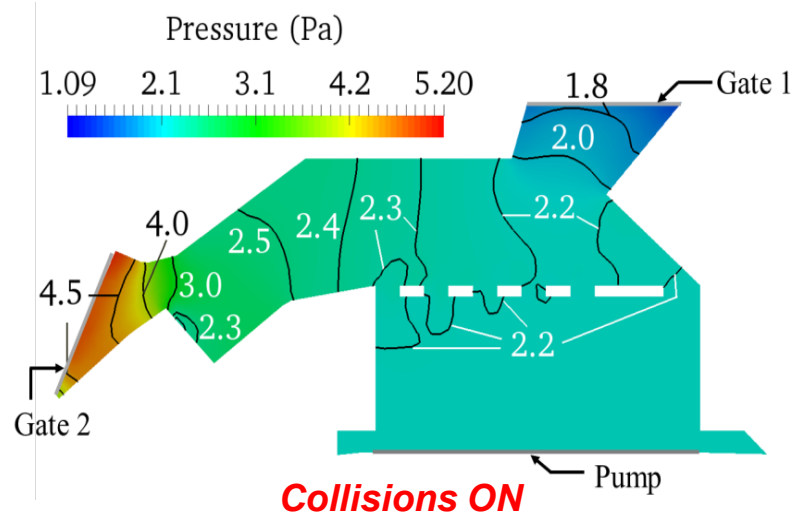
- The SONIC plasma simulations were used to extract DIVGAS boundary conditions.
- The modelled sub-divertor geometry represents a simplified configuration obtained from 3D CAD files.

Effect of collisions in JT-60SA

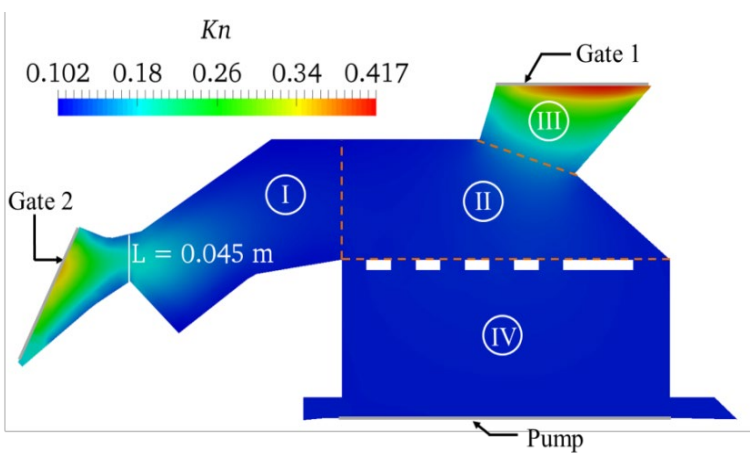
Pressure contours

JT-60SA





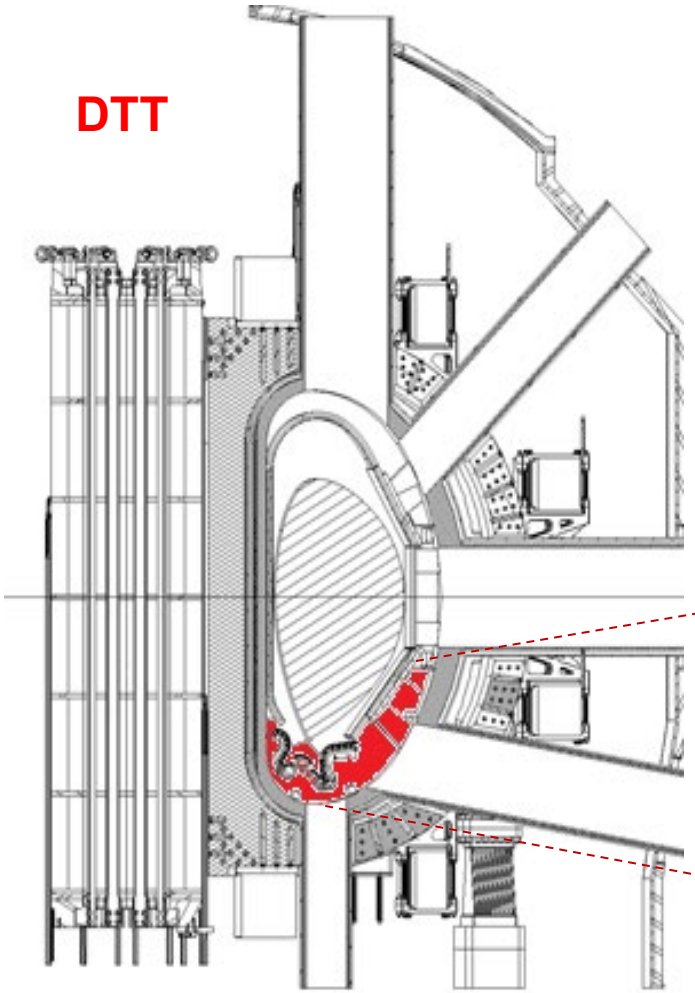
Knudsen number



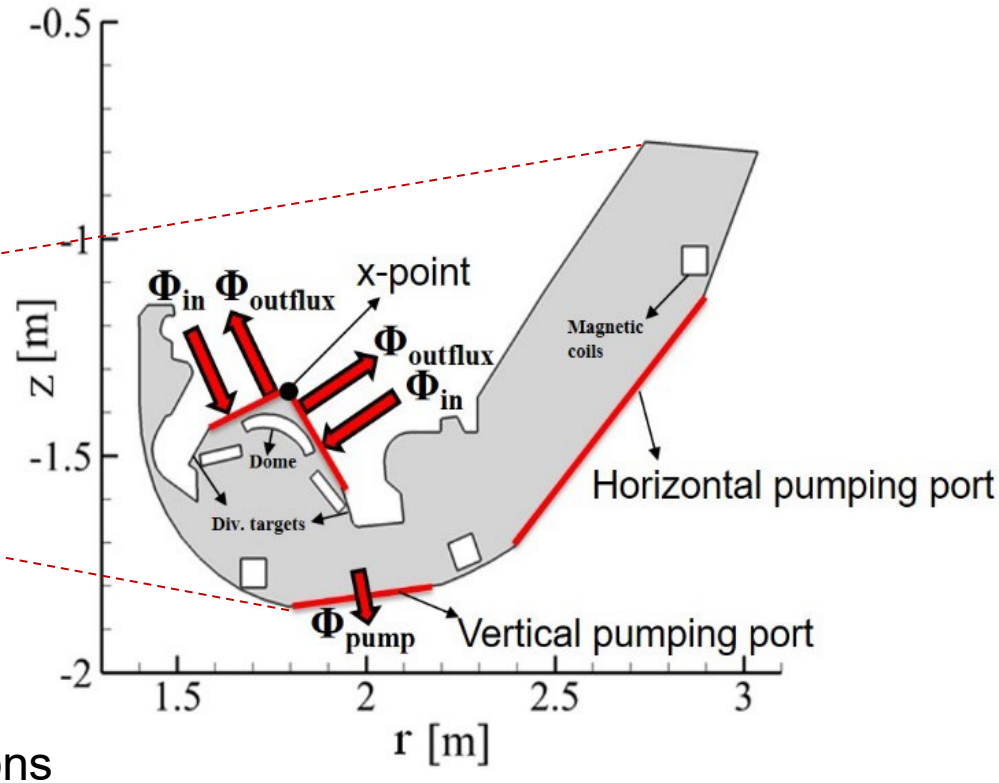
- The neutral collisions increase the pressure by factor of ~2.
- The Knudsen number indicates viscous flow regime (neutral-neutral collisions cannot be neglected)

C. Gleason-Gonzalez et.al, FED, 109-111 (2016) 693-699.

Modelling of DTT sub-divertor



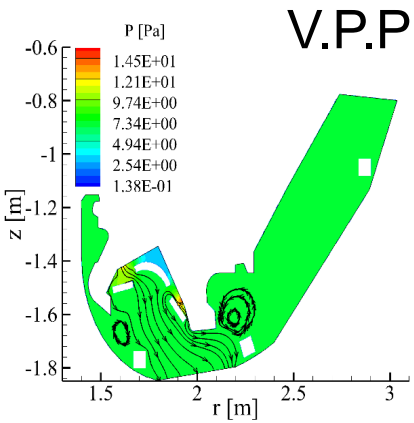
- The SN DTT sub-divertor has been modelled with DIVGAS assuming pumping a) at vertical pumping port (V.P.P) and b) at horizontal pumping port (H.P.P).

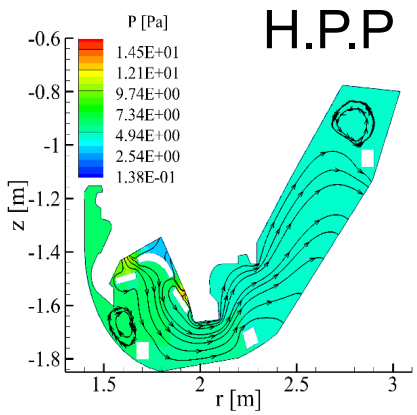


- The SOLEDGE2D-EIRENE simulations were used to extract DIVGAS boundary conditions.

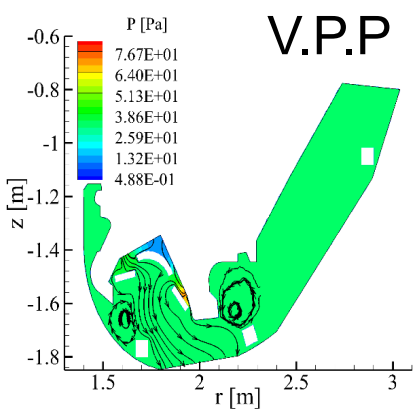
Pressure contours & velocity streamlines

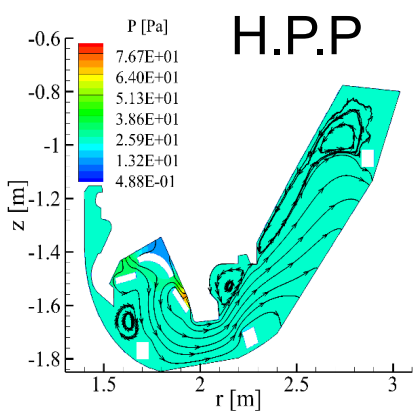
- Low puff. (ξ=0.1)





- High puff. (ξ=0.1)





- Based on the DIVGAS simulations it was decided to use mainly the vertical pumping port for pumping.
- The area of the vertical pumping port had to be increased.

Poster: C. Tantos et al., Self-consistent modelling of the interface between the divertor and the pumping system in DTT

C. Tantos et al., NF, 62(2) (2022) 026038.

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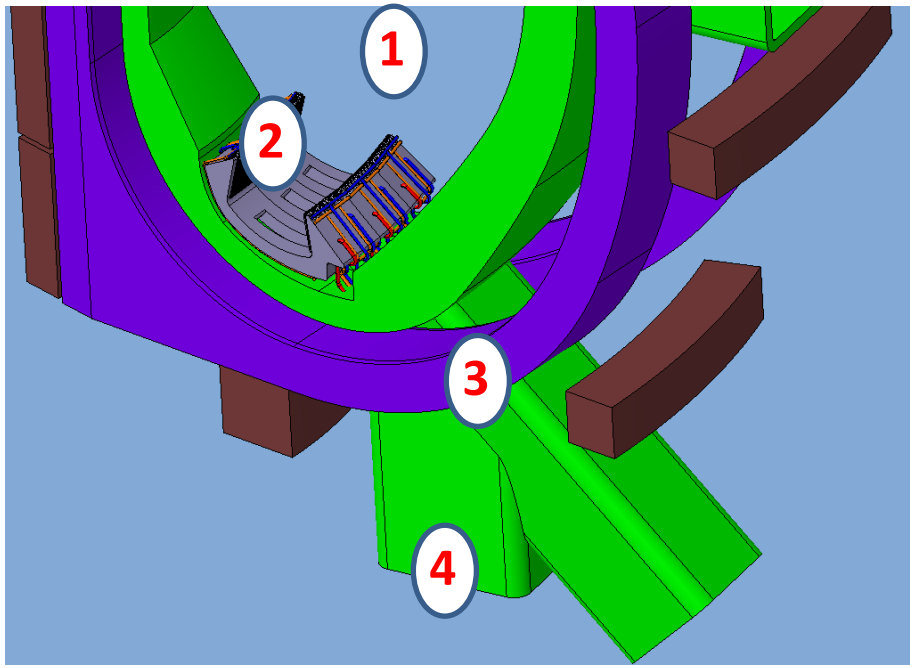
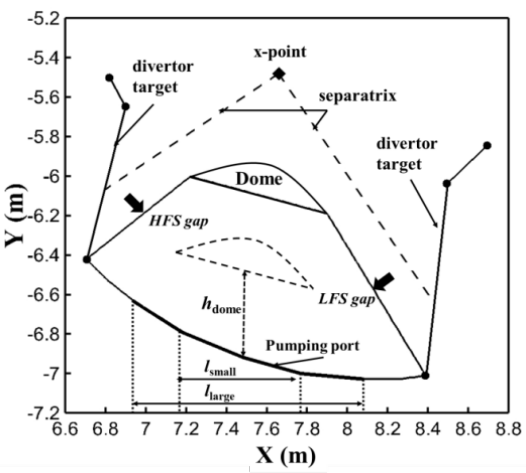
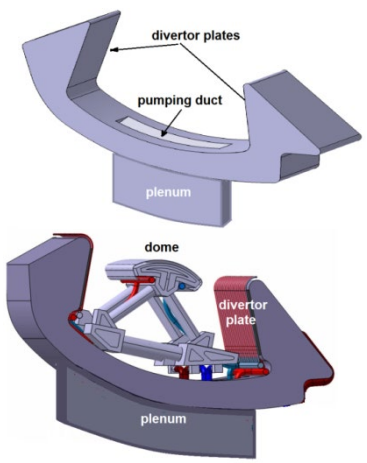
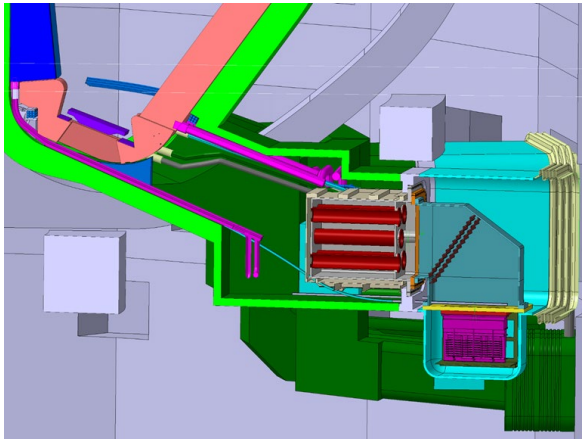
Integrated DEMO divertor workflow



- **Pos. 1**: Extract information of the plasma edge
- **Pos. 2**: Calculate the sub-divertor neutral gas flow for a given divertor geometry and an assumed pumping efficiency (DIVGAS code)
- **Pos. 3**: Include an engineering pump design
- **Pos. 4**: Include the duct losses → physics / engineering self-consistent design point

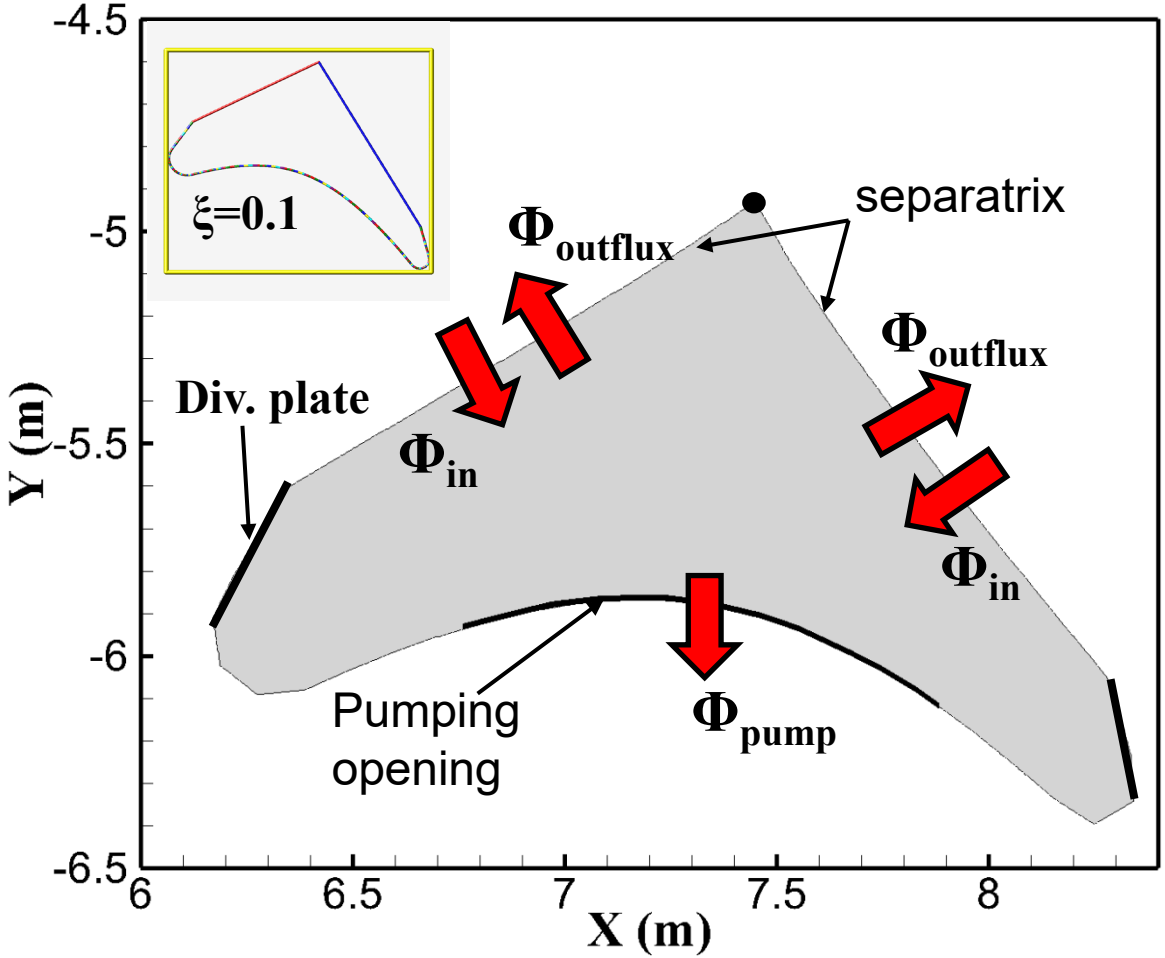




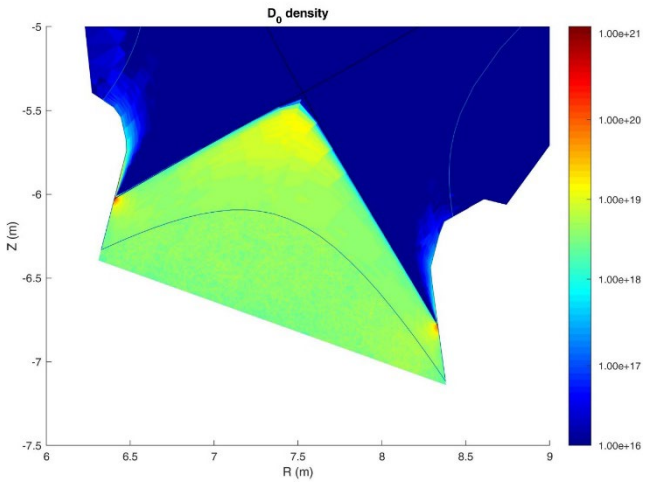


Vacuum pump train integration

Generic DIVGAS model



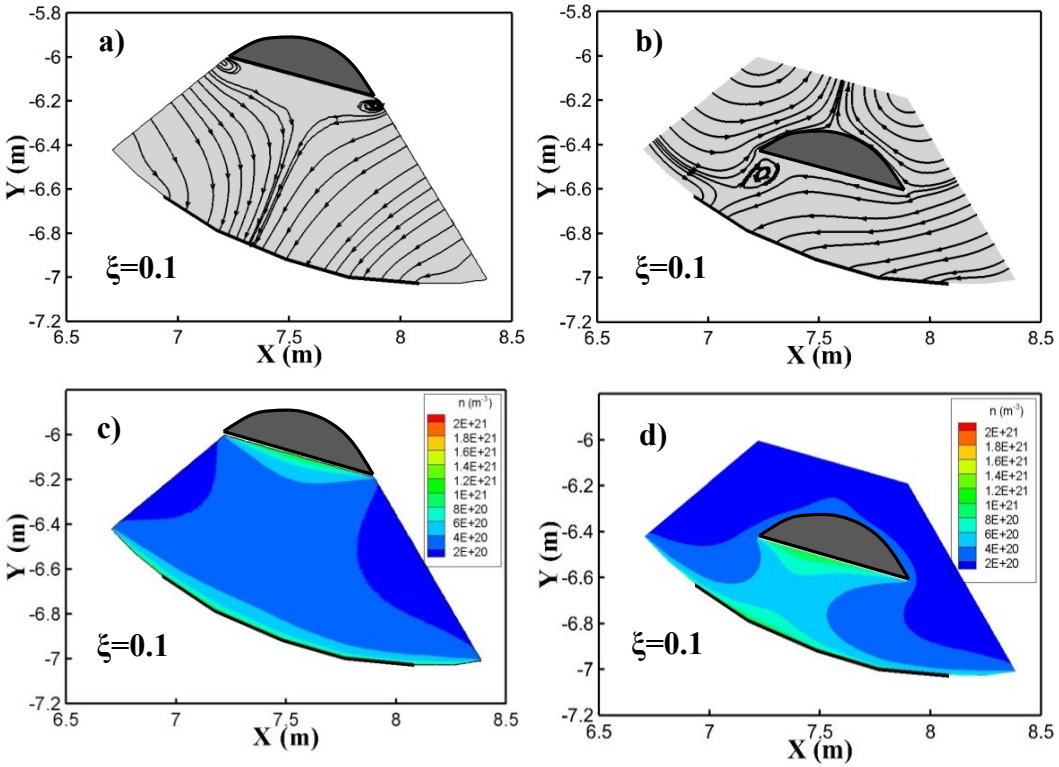
- Species: D_2, D, He, Ar, …
- The particle flux Φ_{in} depends on the imposed plasma BCs
- A capture coefficient $0 \leq \xi \leq 1$ is assumed on the pumping opening.
- May require albedo iteration



- **Mass balance:**

$$\Phi_{pump} = \Phi_{in} - \Phi_{outflux}$$

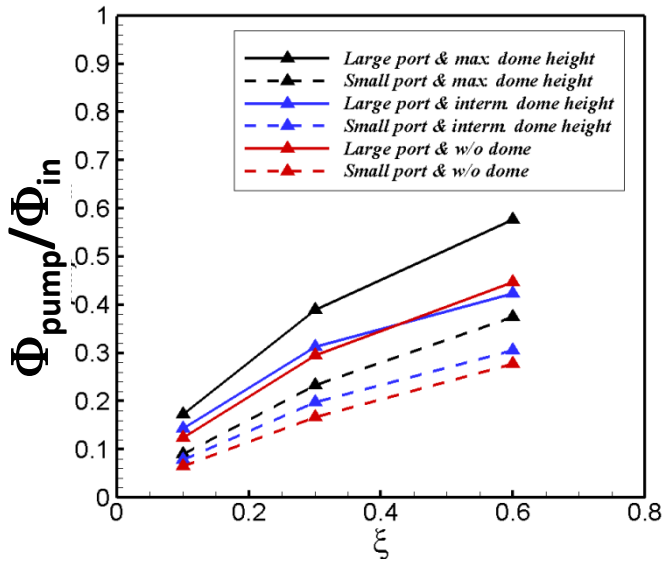
Influence of dome height at DEMO

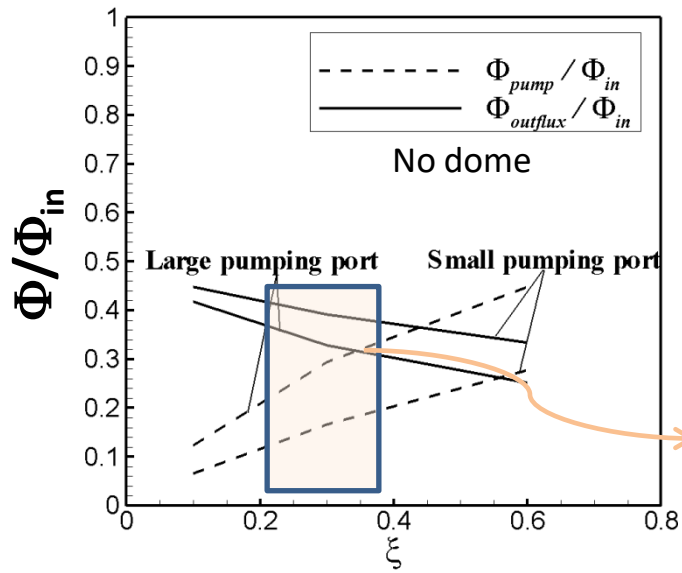


Streamlines *(top) and* ***number density*** *contours (bottom) for maximum (left) and intermediate (right) dome height and large pumping port size.*

- The vortices below the dome are observed.
- The number density below the dome increases by a factor of ~2 as the dome height decreases.
- The same conclusions can be extracted for the case of a liner.

Particle exhaust - Design guidelines





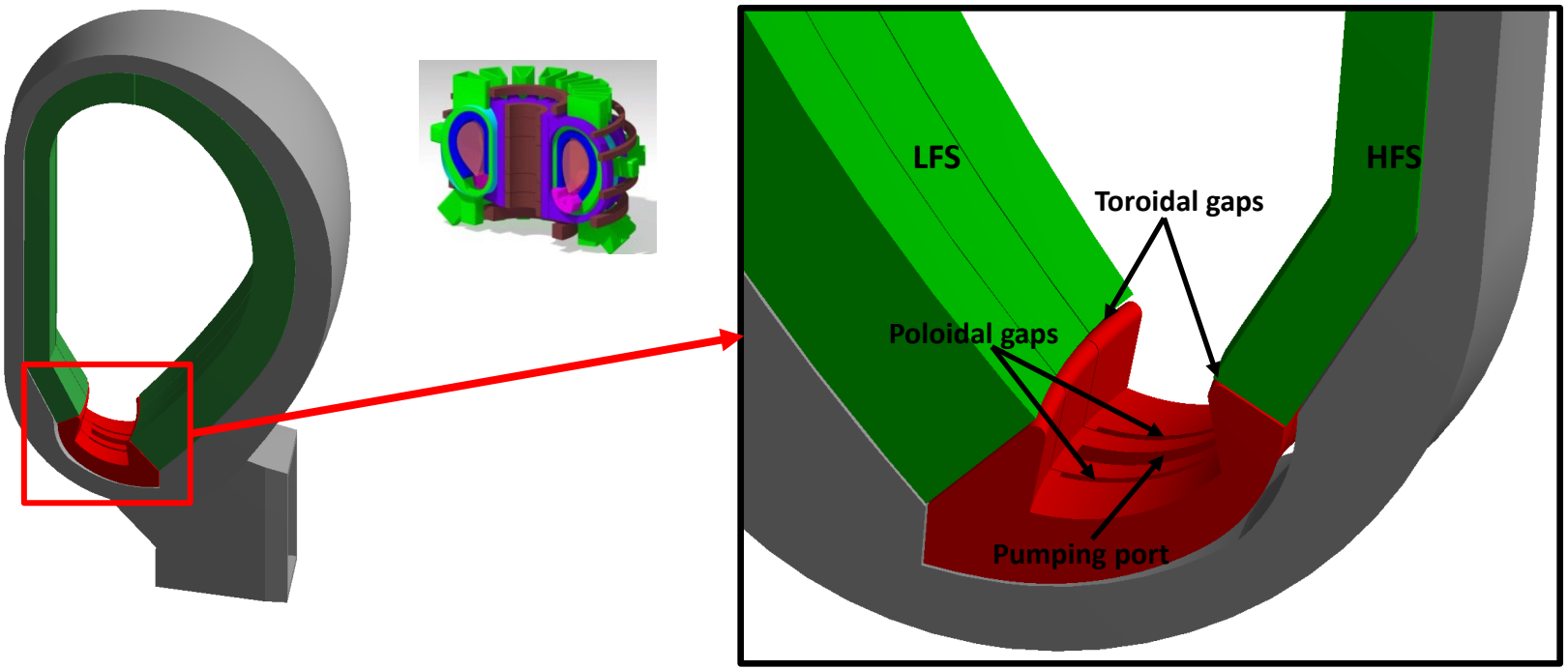
$$\xi = \frac{\Phi}{A \cdot v/4}$$

Design window
→ Pump
→ cross-section A

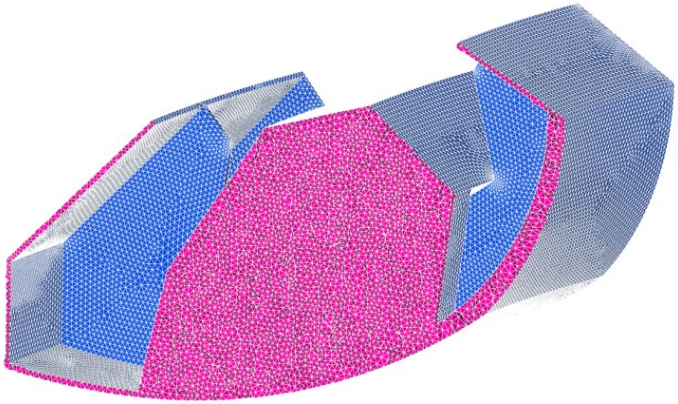
- The pumped flux can be increased by higher heights of the dome, higher impact for higher heights
- The pumped flux depends on the port cross-section and the available pumping probability ξ. The influence of cross-section is stronger than the one of ξ.
- There are cases where the needed ξ becomes unrealistically high, if there is no dome.
- Guideline: First maximize the cross-section, then add a dome, and, if still not sufficient increase ξ.

Chr. Day et al.; IEEE Trans Plasma Science 44 (2016) 1636

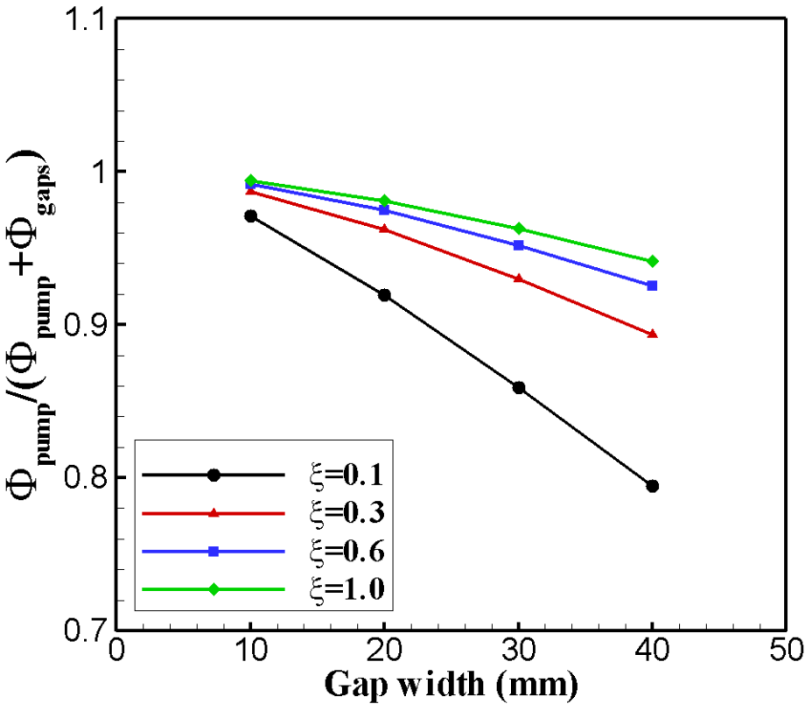
Modelling of 3D DEMO particle exhaust

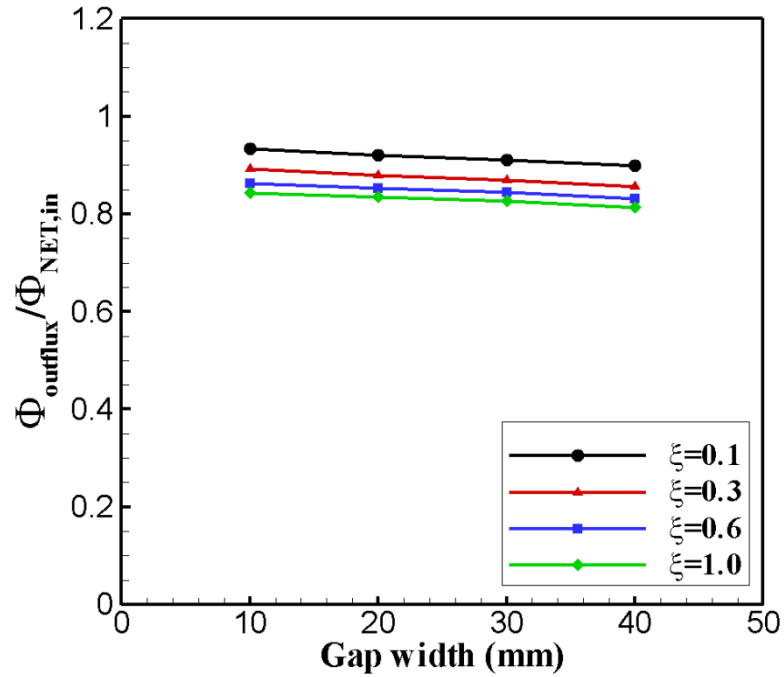


- A 20° degree sector including three divertor cassettes (in red color) as well as the pumping port, the FW (in green) and the vacuum vessel (in grey) has been modelled.
- A 3D DEMO divertor geometry with inter-cassette gaps in the toroidal and poloidal direction is considered.



Influence of gaps on DEMO pumping efficiency

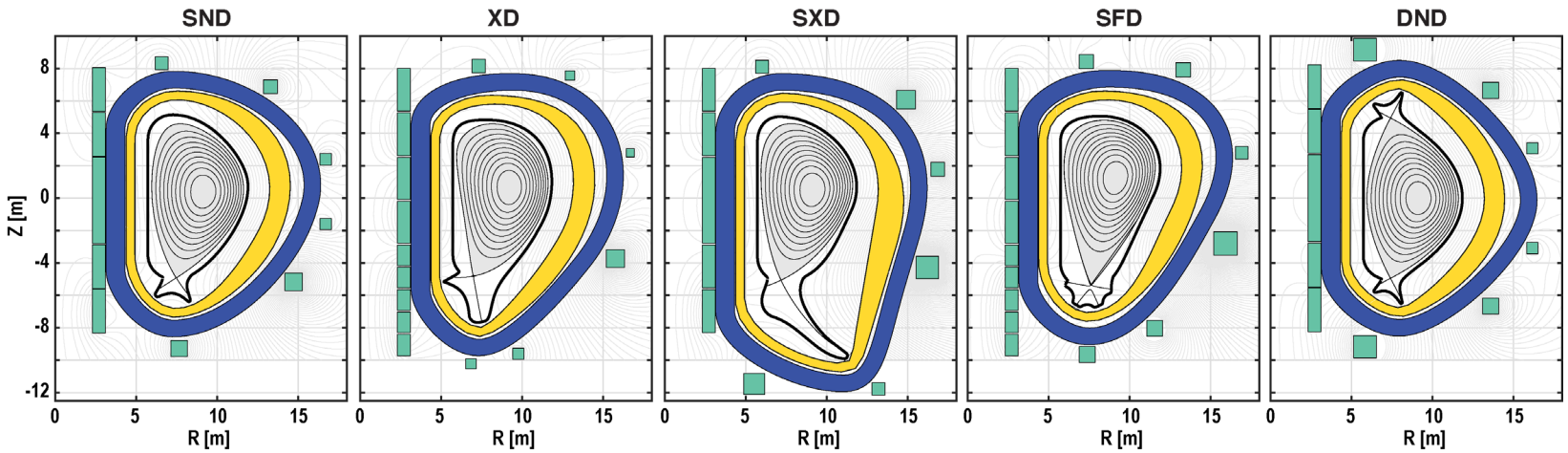


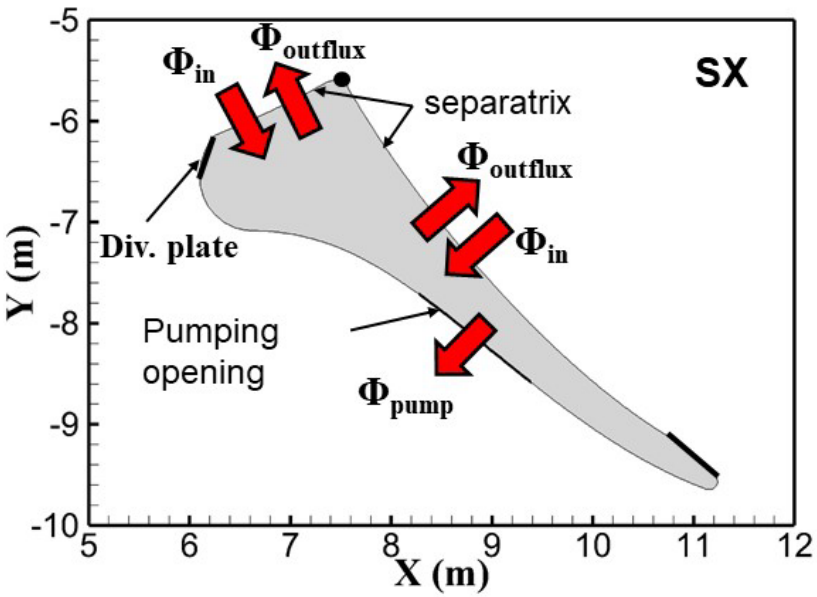


- For the reference case of 20 mm width a reduction on the pumping efficiency of the order of 10% is observed for the lowest capture coefficient ξ=0.1.
- For smaller values of gap width the pumping reduction is negligible, while for large values of the gap width the pumping reduction may reach the value of about 20% for the same small capture coefficient.
- The outflux towards the x-point is independent of the gap width.

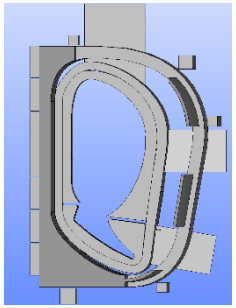
S. Varoutis et.al, NME, **19** (2019).

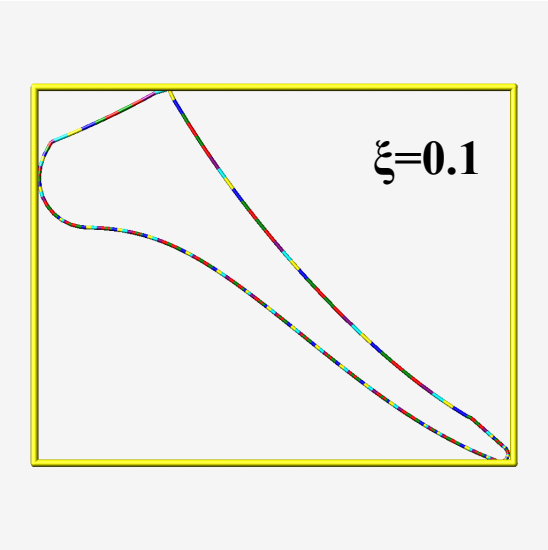
Pumping efficiency for DEMO ADCs





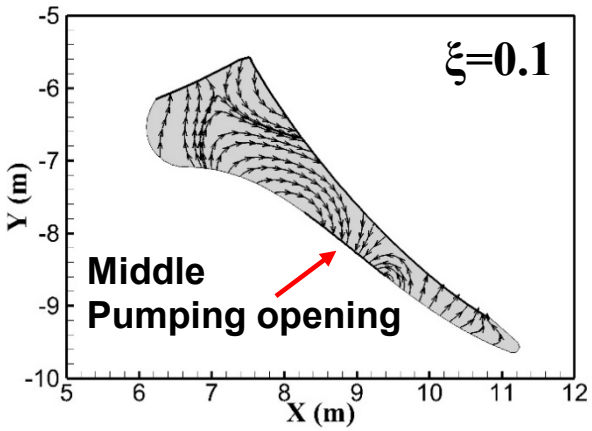
SX: P_{sol}=150 MW, D total puff $1.3 \cdot 10^{24}$/s, Ar total puff $7 \cdot 10^{20}$/s, n_{sep}= $4.11 \cdot 10^{19}$/m³

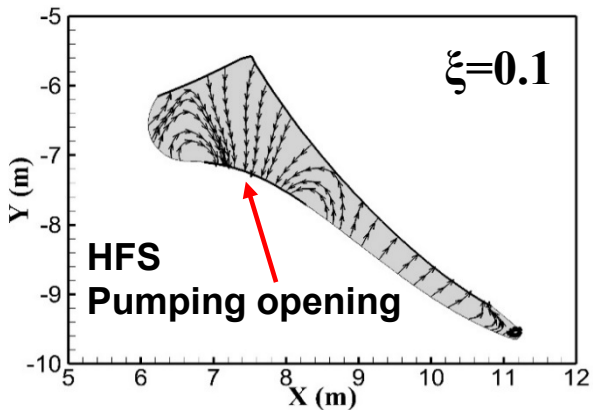


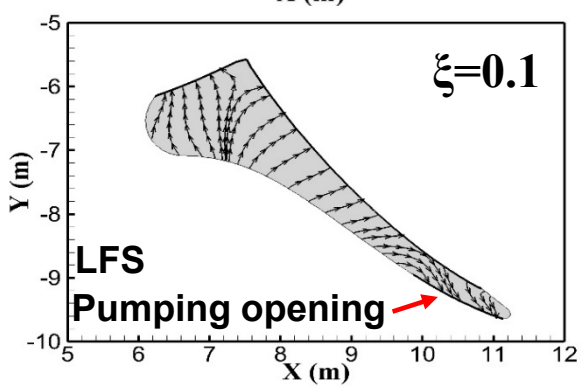


$$\Phi_{pump} = \Phi_{in} - \Phi_{outflux}$$

Position of pumping opening (SX)







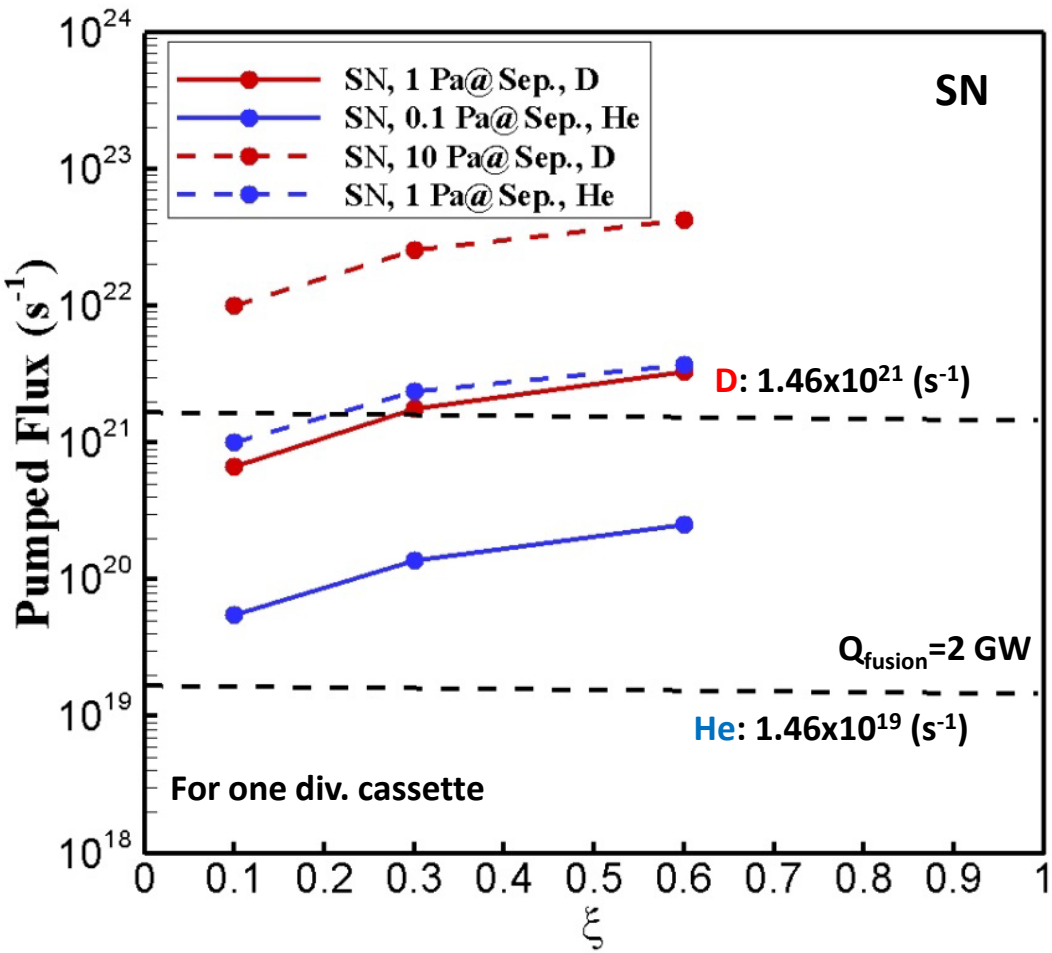
	Middle		HFS		LFS	
	$D+D_2$	He	$D+D_2$	He	$D+D_2$	He
$\Phi_{outflux}$ ($m^{-1}s^{-1}$)	3.38E+23	7.81E+21	3.62E+23	7.82E+21	3.52E+23	7.20E+21
Φ_{pump} ($m^{-1}s^{-1}$)	5.81E+22	5.26E+21	6.60E+22	5.99E+21	6.40E+22	6.23E+21

- Although the differences are quite small and within the numerical uncertainties, the case of having a pumping opening in the middle of the cassette results in lower $\Phi_{outflux}$ for $D+D_2$ compared with the other two configurations, while the case of an opening in the LFS appears to give lower $\Phi_{outflux}$ for helium.

- The cases of an opening in the HFS and LFS result in higher pumped flux Φ_{pump}, compared to the case of an opening in the middle of the cassette (closer to strike points).

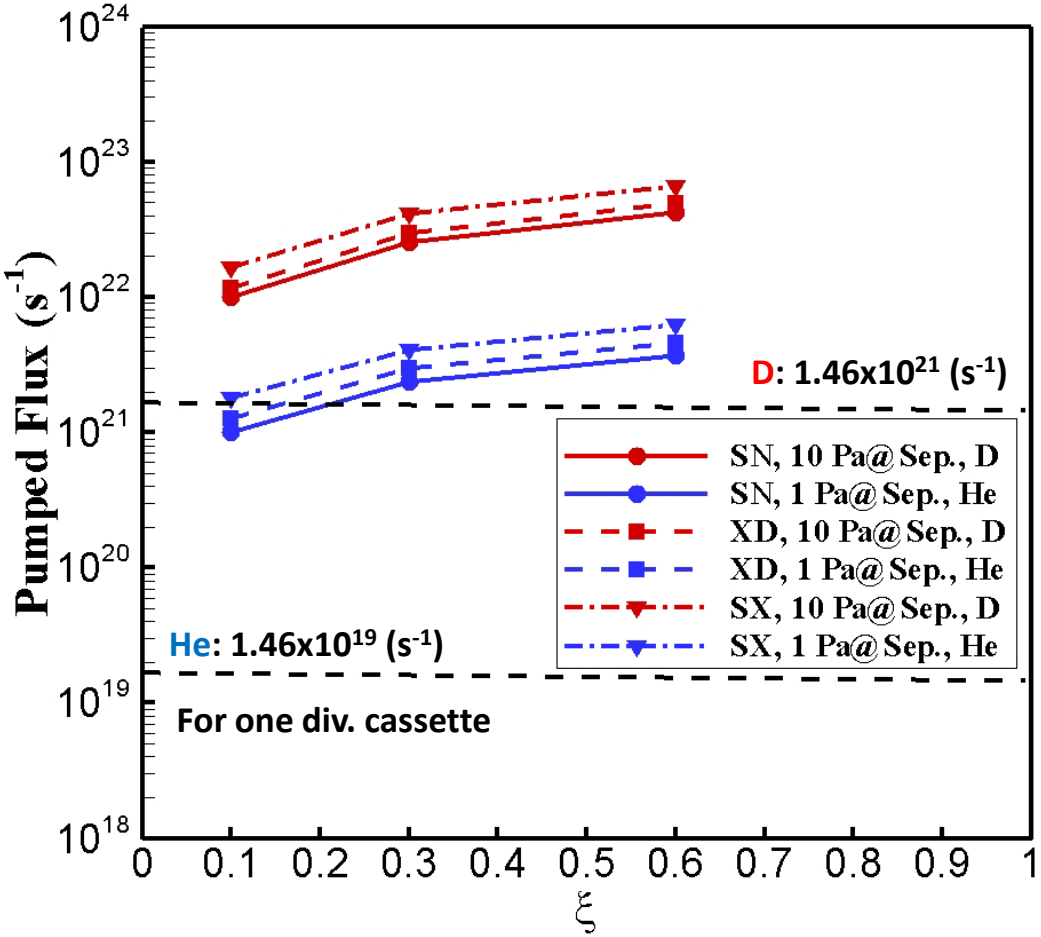
Influence of boundary conditions: separatrix pressure

Current SN design:
$7 \cdot 10^{22}$/s = 140 Pam³/s total



- In general, higher neutral pressure and gas collisionality at PFR, allow for improved helium and fuel removal.
- Helium removal is feasible for both low and high separatrix neutral pressures.
- For the case of gas fuel, pumping can be realised for ξ above 0.3 in the case of low separatrix pressures. For higher separatrix pressures pumping requirement is satisfied for any ξ.

Influence of divertor configuration



- The XD divertor compared with the reference SN case allows for higher neutral compression in the PFR, thus facilitating pumping. For the case of SX divertor this effect is even more pronounced.
- Quantitatively, the pumped flux in SX increases by a factor of ~1.7 in comparison to SN (for both 1 and 10 Pa separatrix pressure)

Conclusions

- By using divertor particle exhaust neutral codes (DIVGAS), the throughput number can be translated in a (cross-section x capture coefficient) number for pumping.
- The neutral-neutral collisions in the sub-divertor area influence significantly the particle exhaust behavior.
- In the case without a dome, a strong outflow of the molecules towards the core is observed – Due to the viscous effects, complex field lines with vortices are expected.
- For an open divertor, namely without dome/liner, the particle exhaust can only be insured with a pumping system of high pumping efficiency.
- It is preferable to have a dome/liner with maximum height and with a large pumping port size - In terms of cost a larger pumping port is more preferable than a very efficient pump.
- The position of the pumping port is preferable to be in the middle of the cassette for reduced outflux.
- The inter-cassettes gaps have a moderate influence on the pumping efficiency.
- A “long-leg” divertor (i.e. SX) has a higher pumped flux compared to the SN divertor (neutral compression due to divertor closure).