An integrated view on high density operation and fuel cycle

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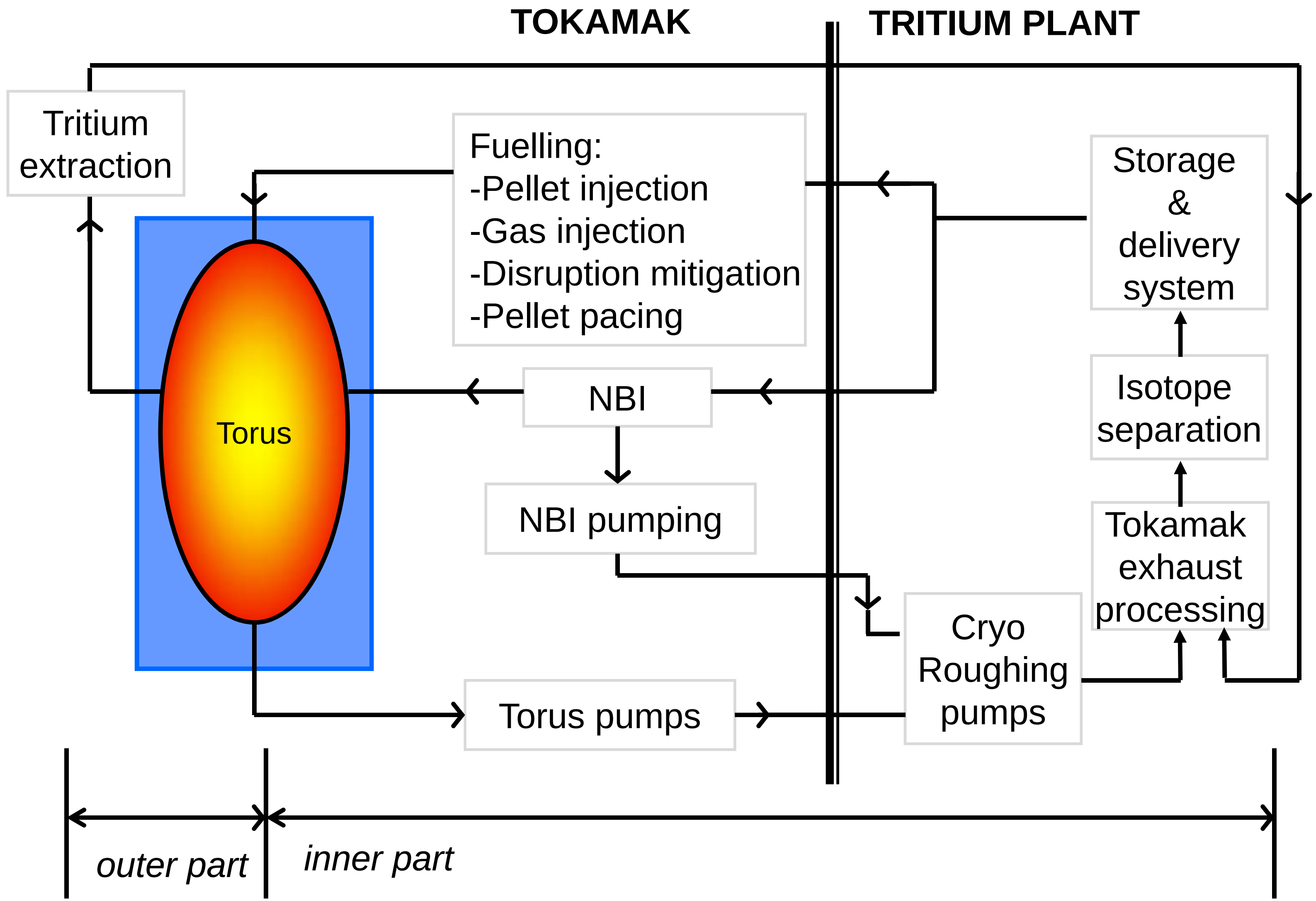
Outline

- Short intro on the fuel cycle
- Example of integrated view: Divertor pumping system
  - ITER situation and limitations
  - Outline of a DEMO suited divertor pumping system.

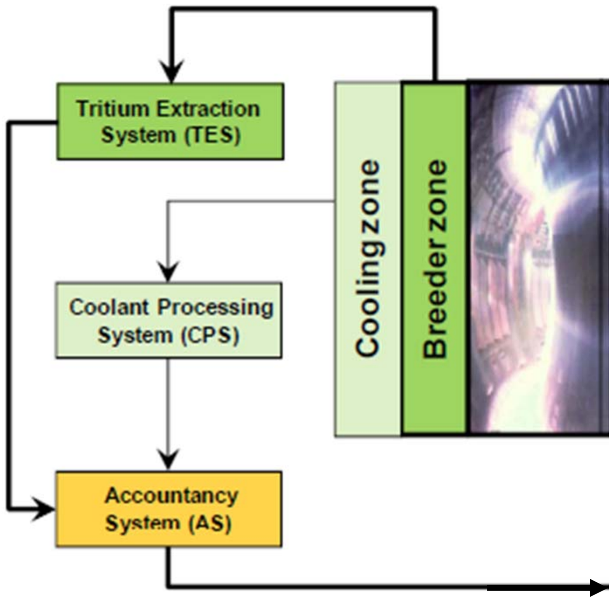
The nuclear fusion fuel cycle (ITER-style)



Existing gaps between ITER and the outer DEMO fuel cycle

~ 5000 MW thermal

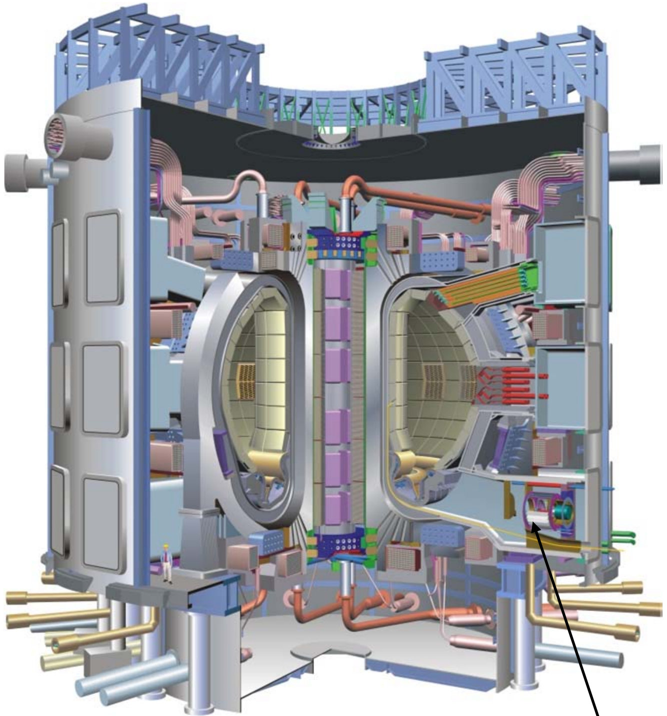
Parameter	ITER	DEMO	GAP
Tritium production	25 mg/day (module)	~ 400 g/day (machine)	~ 10^4
He flow rate in TES	~ 8 - 40 m^3/h	~ 10 000 m^3/h	~10^3
He flow rate in CPS	~ 75 m^3/h	~ 50 000 m^3/h	~10^3

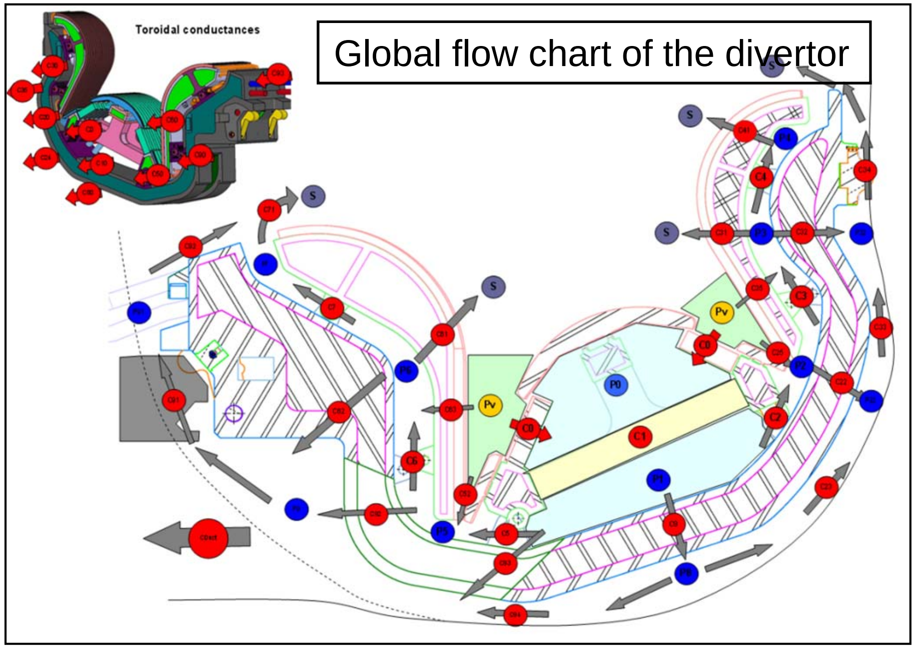


Design to reflect:
- Burn-up fraction
- required TBR
- required tritium processing time → Tritium plant dynamics

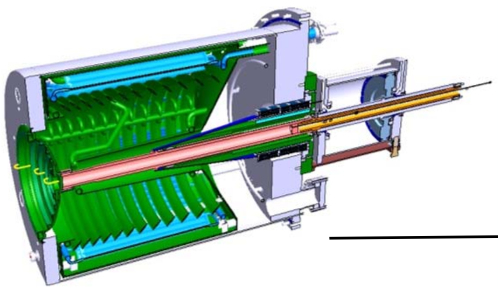
To inner fuel cycle: integraton of divertor and vacuum pumping systems

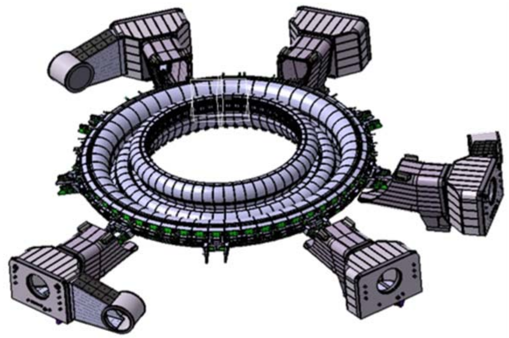
ITER Technologies: Divertor pumping by cryosorption





8 x Torus cryopumps
(1.3 x 1.5 m diam)





What was the reason to go for cryopumping at ITER

- The fuel cycle design was simply based on the defined throughputs at the defined divertor neutral pressures → no integrated view.
- Design driver is the operation during plasma burn. Neutral pressures were specified between 0.25 and 10 Pa.
- ITER asked for large gas throughputs Q (> 200 Pam^3/s) at moderate vacuum → high pumping speeds S=Q/p .

  (But this is an unusual application. These high pumping speeds are normally provided by ultrahigh vacuum pumps → moderate gas throughputs, very low p.)

  → Only turbopumps (small S → high number of pumps), cryopumps and Ti sublimation pumps remain (no getters, ion pumps).
- DT fusion asks for good helium pumping capability → excludes Ti sublimation, excludes cryocondensation.
- DT fusion asks for tritium compatibility → excludes turbopumps
- Fusion asks for operation in magnetic field and under neutrons

  → excludes turbopumps
- And: 4.5 K supply / the cryoplant was there anyway

What did ITER have to accept in consequence

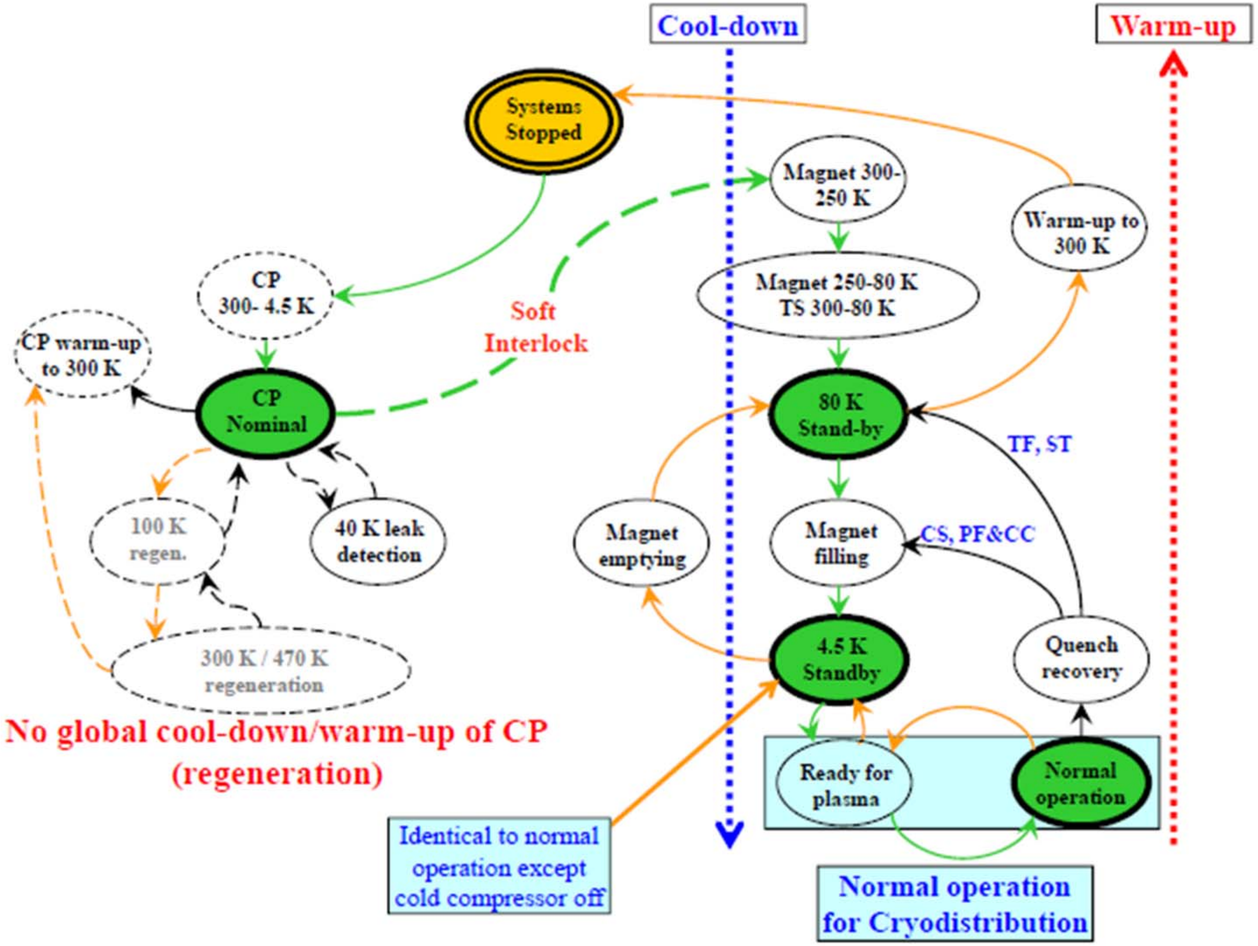
- The pump capacity is limited.
  - This is not a drawback as long as the available capacity is above the administrative (tritium inventory limitation, hydrogen explosion accumulation limitation) limits. This can be / is considered in the design.
- The cryopump is not pumping continuously.
  - This is not a drawback if the between pulse time allows for regeneration of the pumps. This can be/ is considered in the design.
- In consequence, in order to allow for long pulse operation at ITER / very long pulse at DEMO, the number of cryopumps is doubled; at all times, half of them are pumping, the other half is under regeneration.

  (Note: The ITER pumps have to be regenerated every 10 min).
- This resulted in the integration of an inlet valve in front of the cryopump (not for density control!), and thus in space needs so that the pumps are now in ducts at some distance away from the divertor (conductance loss).
- Cryopumps provide a difficult to operate cyclic load to the cryoplant.

Cryopumps are complex cryogenic clients

The cryoplant contributes about 10-15% in the BoP, and the cryopumps represent one fourth of that (averaged).

But they represent about 50% of the dynamic cyclic heat loads and, hence, add a lot of complexity to the plant.

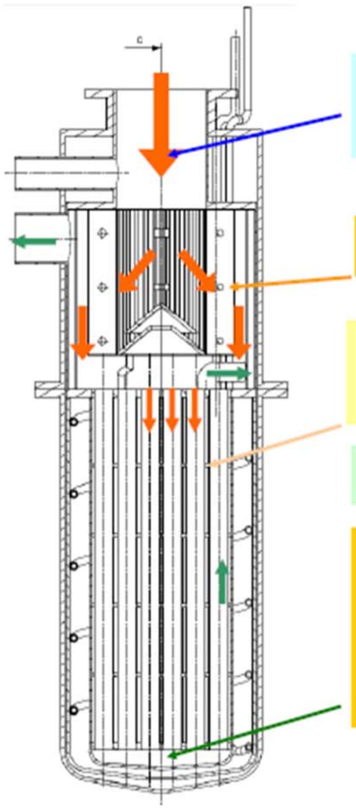


D. Henry, ITER, June 2011.

Cryogenic forevacuum at ITER

A cryopump has to be regenerated, which is done using a forevacuum pump.

For that purpose, ITER is currently developing a second cryogenic pump and a final mechanical pump.



Flow of up to 200 Pa·m^3/s Hydrogen isotopes + He gas mixture at 293 K

Baffle for pre-cooling the gas to about 120 K

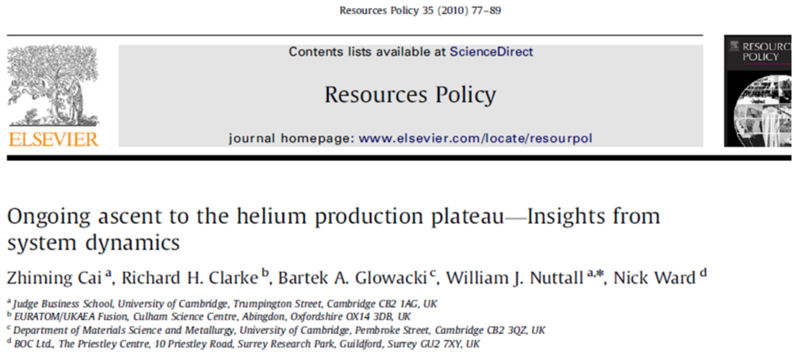
Condenser cooled with ScHe Inlet: ~4.5 K outlet up to 80 K

Hydrogen isotopes and impurities are condensed.

Helium gas becomes separated from the hydrogen isotopes being first dragged by the viscous flow of the condensing stream and then pumped by a mechanical exhaust pump.

L. Baylor, ORNL; R. Pearce, ITER et al.

What does this mean for DEMO?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Ongoing ascent to the helium production plateau—Insights from system dynamics

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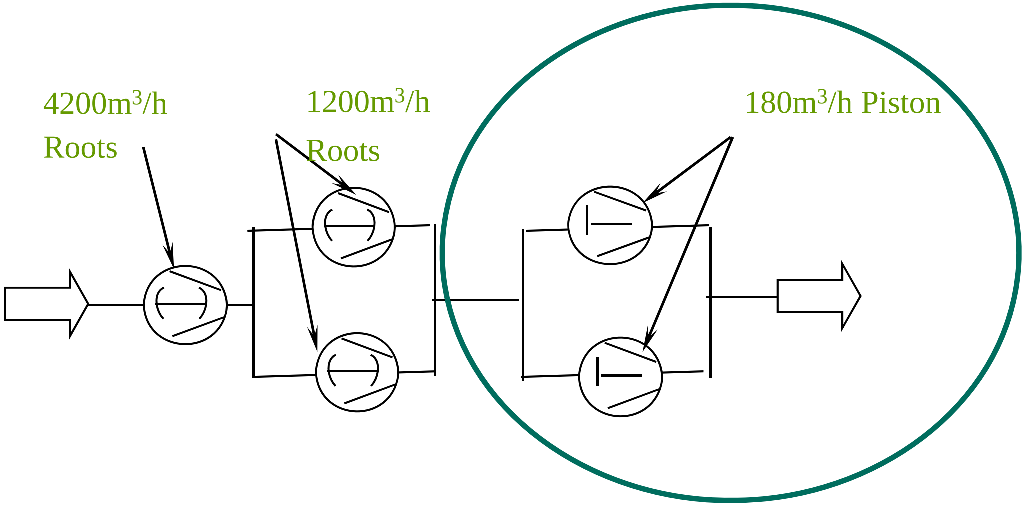
- A solution closest to ITER would be one to ameliorate the cryogenic issues → A cryopump with helium pumping at 20 K (allows to replace helium cooling with liquid neon, liquid hydrogen cooling).
- A much more improved system that would avoid the limitations addressed above would have to meet the following design drivers:
  - (i) Non-cryogenic vacuum
  - (ii) Continuous pumping
  - (iii) Additional separating function
- <u>One</u> solution for (i) + (ii) is to develop a tritium-compatible mechanical pumping train, tuned for minimum inlet pressures and to use this alone during plasma burn operation (and a smaller high vac pump for dwell).
- <u>Another</u> solution is to find an alternative high vacuum pumping system, which integrates (iii) as well.

Mechanical pump development

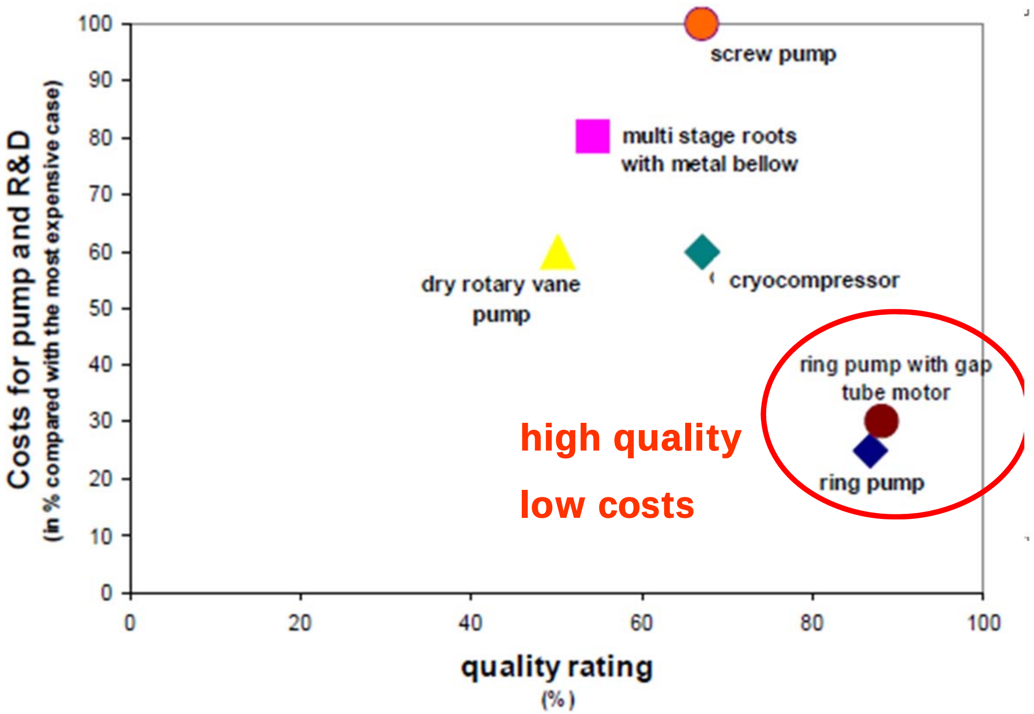


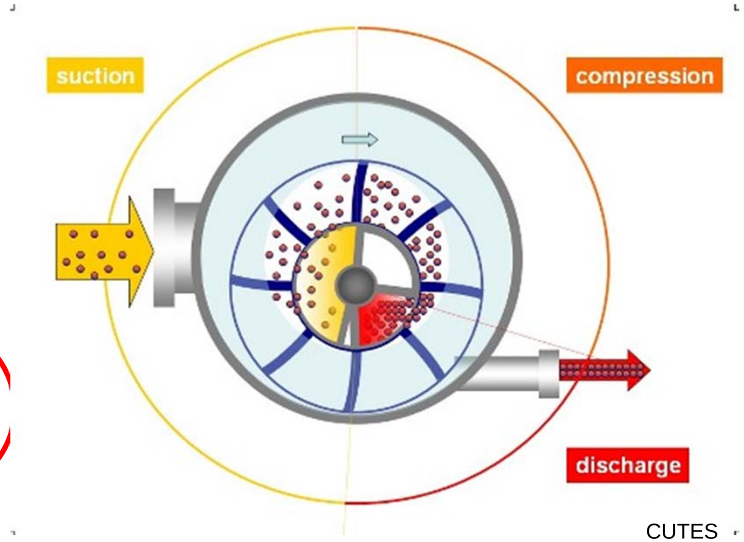
The final stage of the pump train (piston pump) will (most probably) be also needed (means: developed) for the ITER solution.

The European approach to develop a tritium-compatible ferrofluidic seal was not successful after several years of R&D.
This was one of the reasons for ITER to start to develop a cryogenic forevacuum pump, which is believed to work (Based on JET experience).

There are options!

Found in a SWOT and pairwise comparison approach exercise:
Liquid ring pump for fusion application





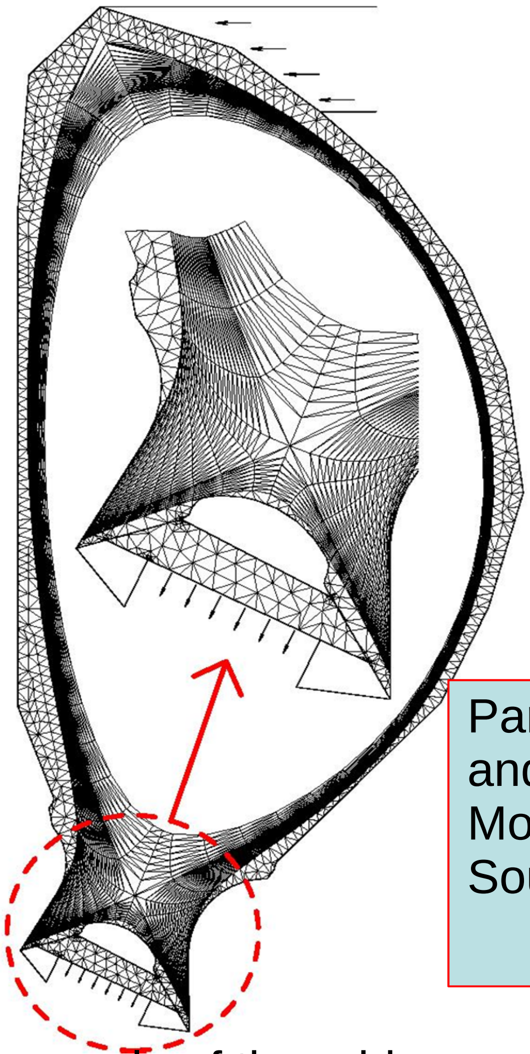
Tritium-compatible liquid: *mercury*
Liquid compressant , Liquid sealing , Liquid cooling.
Industry interest exists.

Ultimate inlet pressure 100 Pa. Is this feasible with the divertor?

Divertor modelling: B2-EIRENE (SOLPS 4.x, 5.x)

Karlsruhe Institute of Technology

In order to identify possible divertor pressures



An example of the grid

2D finite-volume plasma transport code (**B2**)

Plasma Parameters

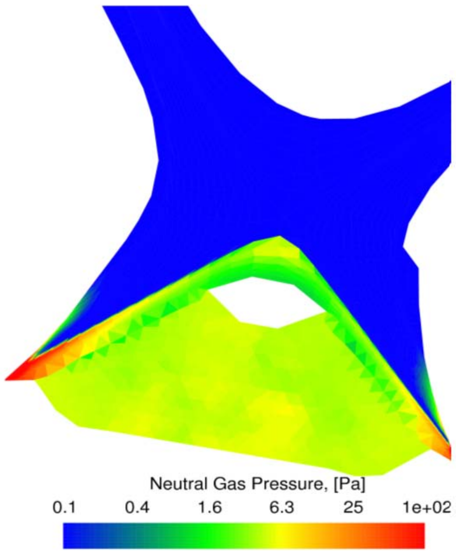
3D Monte-Carlo neutral transport code (**EIRENE**), BGK based

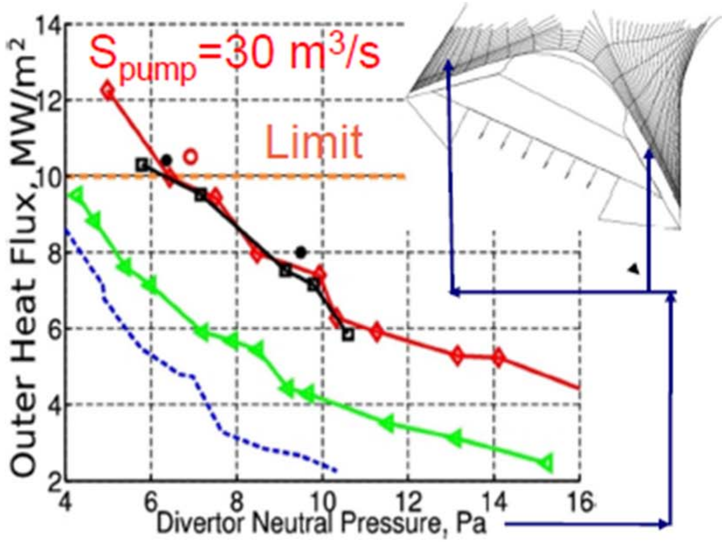
Particle, Energy and Momentum Sources

See: Reiter D., Baelmans M., Börner P., Fus. Sci. Tech, 47, 173 (2005)

JÜLICH FORSCHUNGSZENTRUM

What neutral pressure is achievable?





Peak Target Heat Flux: one of the critical parameters of the design

--- ITER model before 2004
— ... + Neutral-Neutral Collisions
— ... + Detailed Molecular Kinetics
— ... + Radiation Opacity

Strong effect of Neutral-Neutral collisions (blue vs. green)!

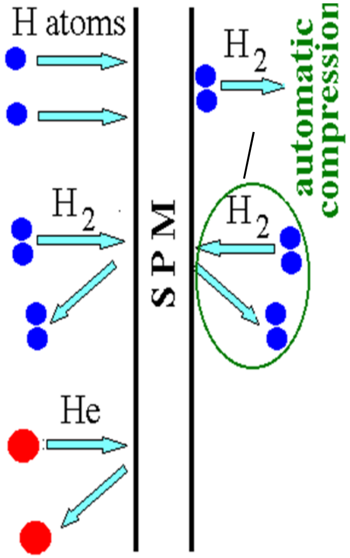
Vladislav Kotov, FZJ, 2007.

→ The 100 Pa seem to be difficult to achieve for the ITER type divertor.

→ *But this situation may be different for other magnetic configurations of DEMO.*

→ To get a more accurate description of the neutral gas flow field, the BGK approximation shall be used by accurate DSMC (task under preparation)

What happens if the final DEMO divertor will not provide sufficiently high neutral pressures?

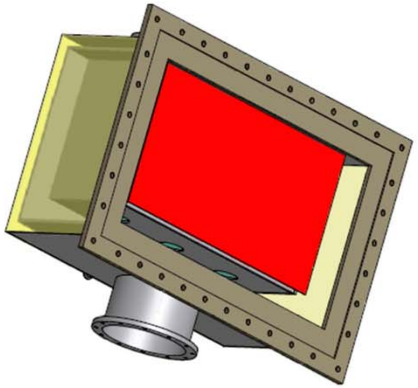


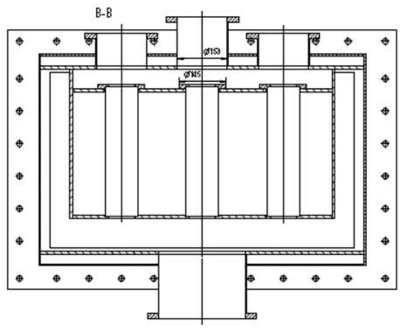
Hydrogen Atomizer

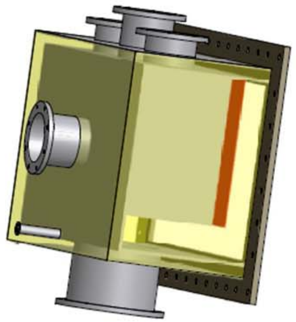
A.I. Livshits and co-workers

Use of **superpermeable metal foil pumps to separate and provide the requested (moderate) compression for hydrogen:**

- compresses hydrogens which pass the foil
- and separates hydrogen from all other gas species (for which the foil is not permemable).
- and purifies the hydrogen.
- This pump concept has a very dynamic characteristic → offers opportunities for plasma control and direct DT recycling close to the divertor.





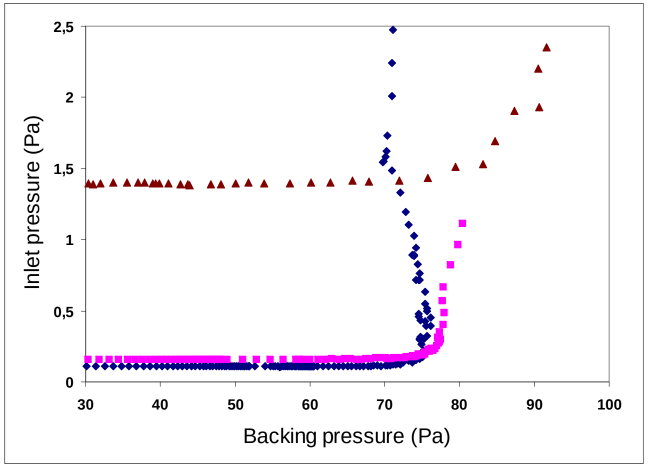


KIT conceptual design

But how is then helium pumped?

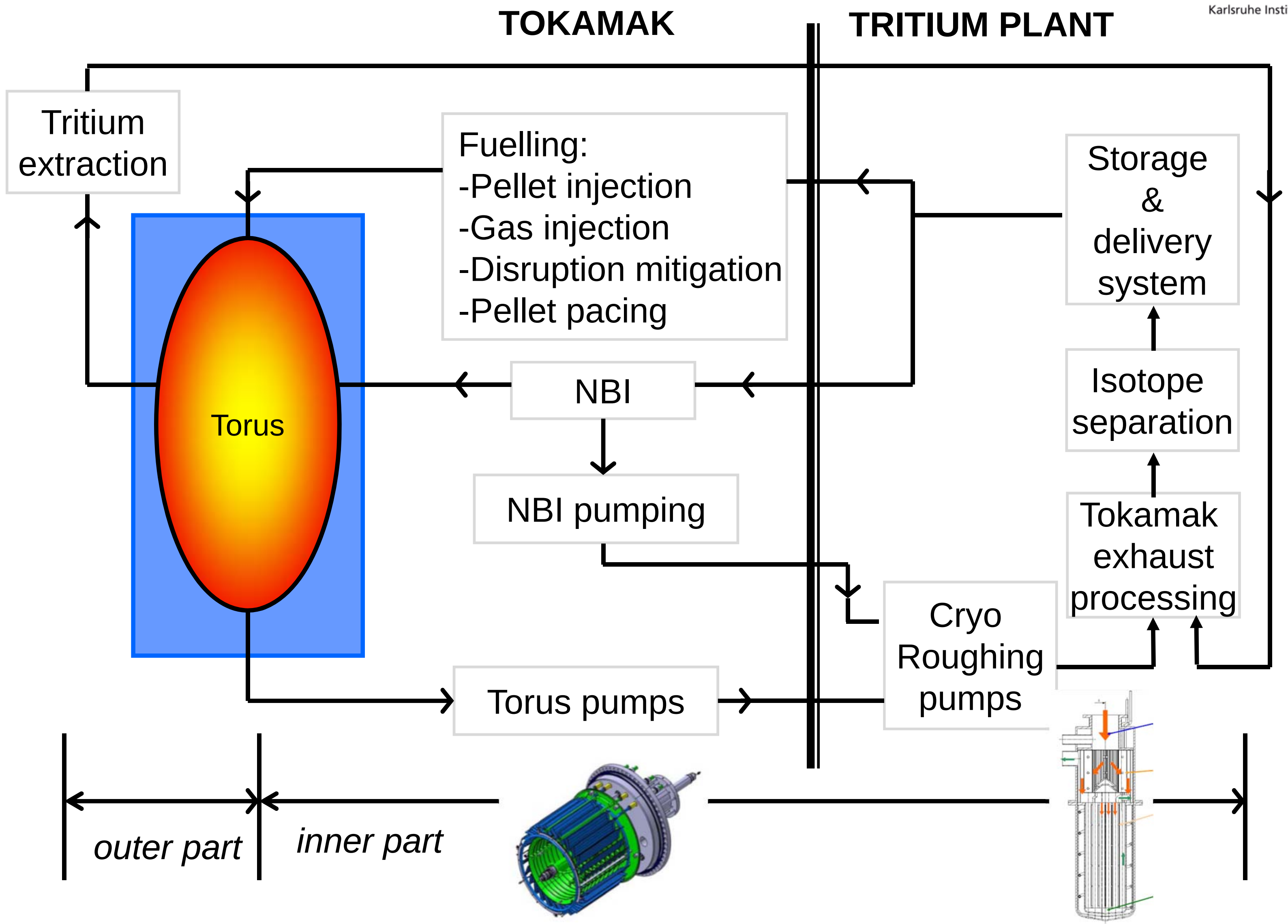
A complementing solution can be found in a **vapour diffusion pump to compress helium**. The liquid/vapor would again be mercury (unmagnetic (as carbon)), as already used in the ring pumps.

- Continuous working pumps
- No cryo-infrastructure necessary
- If the interior parts are properly modified: Excellent handling of untypically high inlet pressures (Pa range) ..
- at high outlet pressures (allows for the liquid ring pump to take over)
- Scale up to very large pumps is easily possible

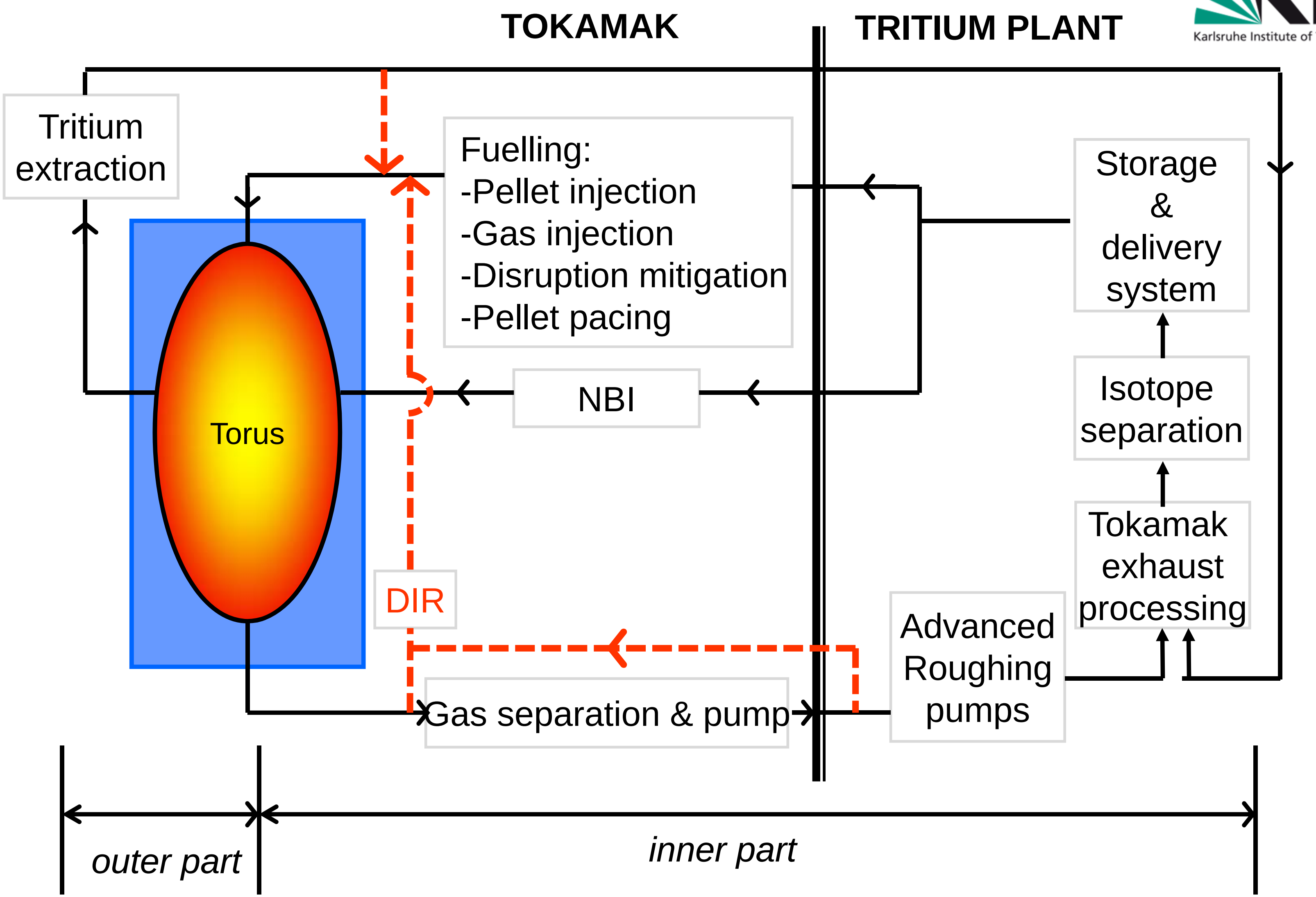


(Helium on mercury)

The ITER fuel cycle



Advanced cycle for a power plant



Direct Internal Recycling: He and hydrogens will be separated, tritium plant is reduced.
Advanced roughing pumps: Working continuously, tritium-compatible, cryogen-free.

Conclusions

- This talk illustrated the integration of the inner fuel cycle with the divertor.
- The ITER divertor pumping systems based on cryopumping are well chosen for ITER but not suited for extrapolation to DEMO.
- A versatile advanced pumping concept which allows for Direct Internal Recycling (DIR) has been developed, which has mainly three elements:
  - A mercury vapor diffusion pump for vessel pump-down and primary pumping,
  - a mercury driven liquid ring pump for compression to atmosphere.
- It is cryogen-free.
- It is continuously pumping.
- It is tritium compatible.
- The use of a superpermeable metal foil module separates sharply hydrogens for direct recycling from the other gases.
- For sufficiently high divertor pressures, the diffusion pump can be bypassed by the (metal foil + liquid ring pump) combination.
- Integrate physics and engineering at an early stage!