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Tritium processing technology developments at KIT for nuclear fusion reactors

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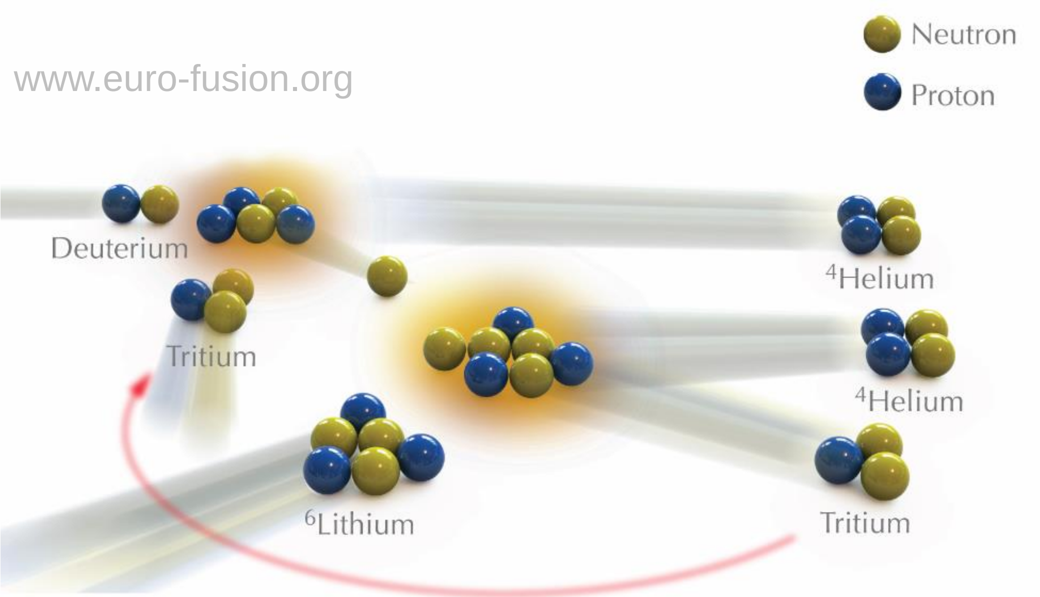
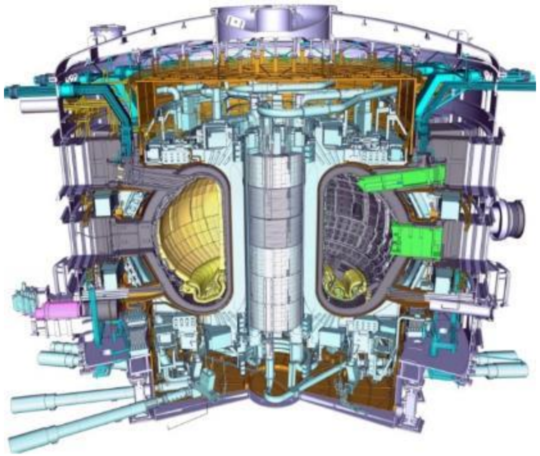
- 1st part: Short introduction to nuclear fusion + fuel cycle
- 2nd part: Vacuum pumps for tritium processing: New developments at KIT
- 3rd part: Isotope separation technologies: Hydrogen separation and lithium enrichment

Short introduction: Nuclear fusion





ITER experimental reactor (under construction in Cadarache, France):
- Machine height: 28 m
- Machine diameter: 29 m
- Mass: > 28.000 tons

- Fusion as new source of energy for the future (2050 –)
- In Europe, work coordinated by the EUROfusion consortium
- Reaction conditions in fusion reactors: 100 Mio. K

→ Plasma containment in vacuum

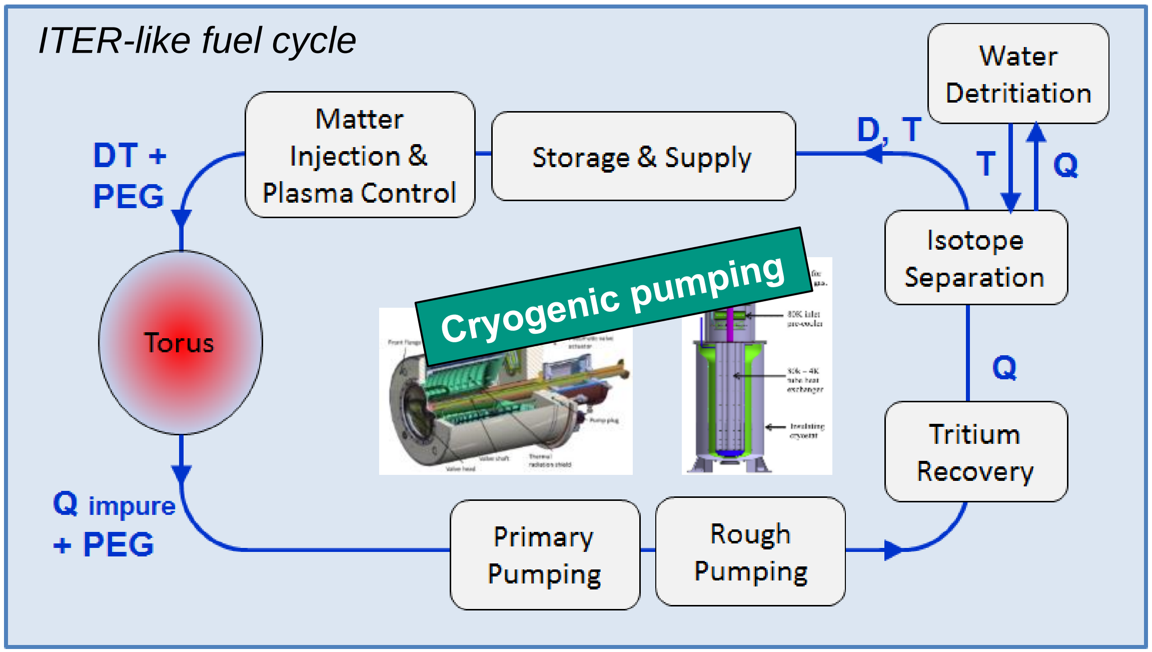
→ Helium (and impurities) must be pumped out continuously

→ **Vacuum pumping and fuel cycle needed**

Vacuum pumping in fusion reactors

- The vacuum pumping system in DEMO (= first reactor that demonstrates the production of electric energy) must fulfill the following main requirements:
  - Keep the required vacuum inside the torus against a gas load (390 Pa m^3/s) during a long (2 hours) burn phase
  - Provide vacuum conditions for plasma pulse start-up (10^{-3} Pa region) in a given time (1000 seconds) during the dwell phase

→ Large vacuum system needed



- In an ITER-like fuel cycle, all pumped gases must be processed in the tritium plant
- > 90% of pumped gas is unburned fuel (i.e. a DT mixture)

→ Very large process facilities

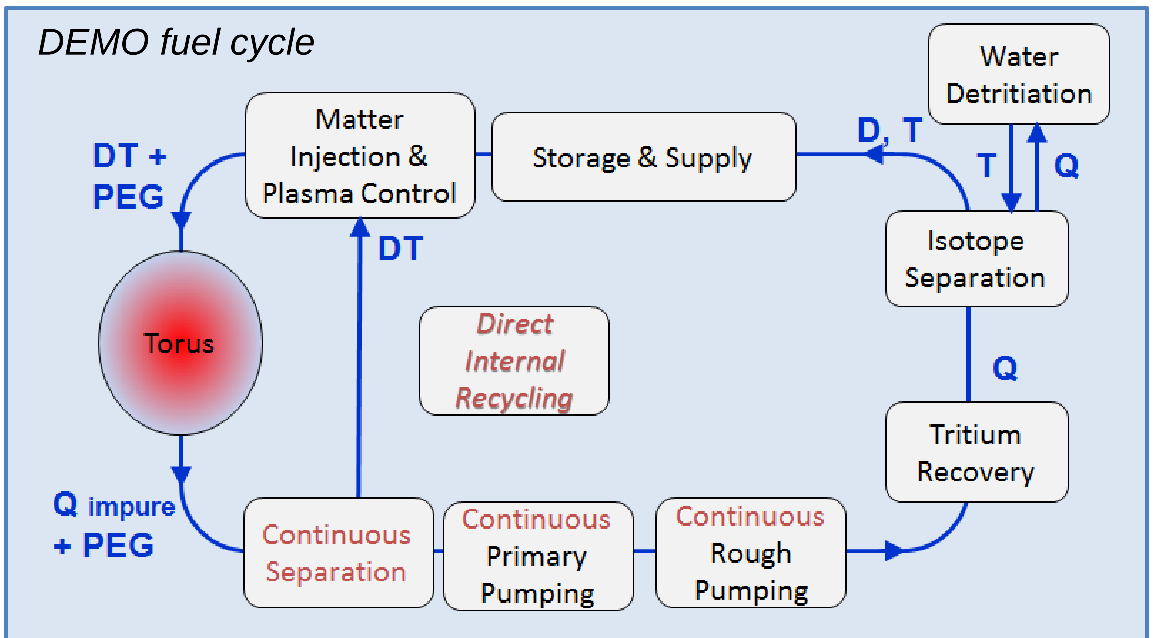
Tritium inventory issues in the fuel cycle

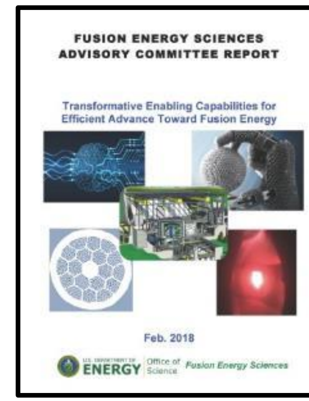
- Problem with large vacuum systems/processing plants: Large flows lead to large tritium inventories (assuming an ITER-like solution with cryogenic pumps)

→ Issues with tritium availability, safety, economical attractiveness,…

- Solution: Development of a novel fuel cycle concept with Direct Internal Recycling (DIR) and continuously working, non-cryogenic pumps

→ **Novel concept foreseen for the EU-DEMO reactor**





FESAC (DOE) Panel has acknowledged this work and sorted the metal foil pump technology as one of the ‚Grand Challenges in Fusion Science and Technology'

Vacuum pump developments for the EU-DEMO (1)

Challenges on vacuum pumps in fusion:

- Strong and changing ambient magnetic fields and neutronic for primary pumps
- Dust & dirty environment for primary pumps
- Very high pumping speeds over a wide pressure range required (~ 600 m^3/s @ 1-10 Pa during plasma operation or < 10^{-3} Pa in between the pulses) for primary pumps
- High safety requirements (potential water leaks, loss-of-vacuum accidents, seismic events, disruptions, etc.)
- Tritium pumping (chemically very reactive, radioactive)
- Pumping of mainly light gases (50% tritium, 50% deuterium, traces of helium + impurities)

Design consequences:

- Moving components (overheating due to eddy currents, levitation problem, dust problem) not allowed for primary pumps
- Polymers (would decompose due to tritium decay) not allowed

→ **New developments needed**

Vacuum pump developments for the EU-DEMO (2)

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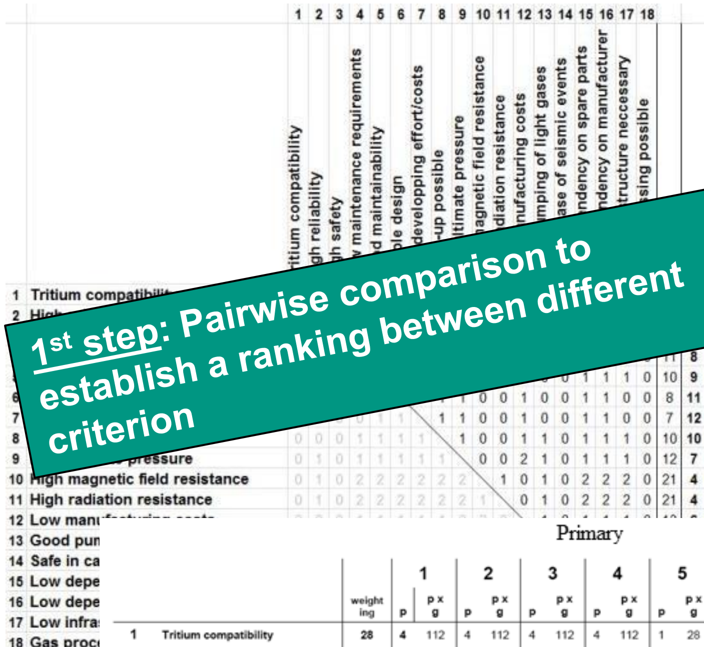


1st step: Pairwise comparison to establish a ranking between different criterion

- An assessment of available pumping solutions has been done based on an unbiased theoretical approach [1]
- As starting point, the well known vacuum pump tree has been chosen
- As result, a table showing the quality of the solution and the costs for development and procurement was obtained

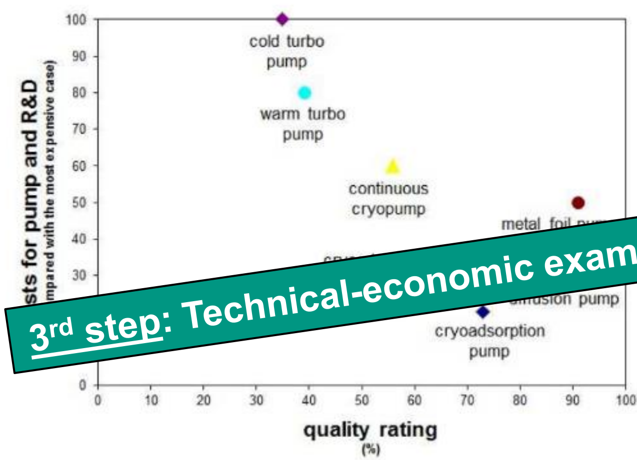
Primary

		weighting	1 p	1 p x g	2 p	2 p x g	3 p	3 p x g	4 p	4 p x g	5 p	5 p x g	6 p	6 p x g	7 p	7 p x g	8 p	8 p x g
1	Tritium compatibility	28	4	112	4	112	4	112	4	112	1	28	1	28	4	112	4	112
2	High reliability	21	3	63	3	63	2	42	2	42	0	0	0	0	3	63	4	84
3	High safety	32	4	128	4	128	4	128	4	128	3	96	3	96	4	128	4	128
4	Low maintenance requirements	11	4	44	1	11	1	11	1	11	0	0	0	0	4	44	4	44
5	Good maintainability	10	4	40	2	20	2	20	2	20	2	20	2	20	3	[illegible]	[illegible]	30
6	Simple design	8	4	32	3	24	3	24	1	8	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	32
7	Low developing effort/costs	7	4	28	3	21	2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	14
8	Scale-up possible	10	4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	40	3	30
9	Low ultimate pressure	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	3	36	3	36	3	36
10	High magn[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2	42	0	0	0	0	4	84	4	84
11	High radiat[illegible]	[illegible]	[illegible]	[illegible]	4	84	4	84	4	84	1	21	1	21	3	63	3	63
12	Low manuf[illegible]	13	1	13	0	0	0	0	0	0	1	13	1	13	3	39	3	39
13	Good pumping of light gases	17	0	0	2	34	2	34	0	0	1	17	1	17	4	68	4	68
14	Save in case of seismic events	28	4	112	4	112	3	84	3	84	1	28	1	28	4	112	4	112
15	Low dependency on spare parts	11	4	44	3	33	3	33	3	33	0	0	0	0	4	44	4	44
16	Low dependency on manufacturer	11	4	44	3	33	2	22	2	22	3	33	0	0	3	33	4	44
17	Low infrastructure necessary	11	0	0	0	0	0	0	0	0	4	44	3	33	4	44	3	33
18	Gas processing possible	34	3	102	2	68	2	68	1	34	4	136	4	136	4	136	4	136
	SUM	306	940		894		817		683		479		428		1114		1133	
	quality rating W =		76,8		73,0		66,7		55,8		39,1		35,0		91,0		92,6	

2nd step: Calculate a quality rating

Roughing

1 p	1 p x g	2 p	2 p x g	3 p	3 p x g	4 p	4 p x g	5 p	5 p x g	6 p	6 p x g	7 p	7 p x g
1	28	1	28	1	28	1	28	4	112	4	112	3	84
2	42												
2	64												
1	11												
1	10												
2	16												
1	7												
0	0												
0	0												
1	21												
1	21												
1	13												
3	51												
3	84												
1	11												
3	33												
4	44												
4	136												
592													
48,4													

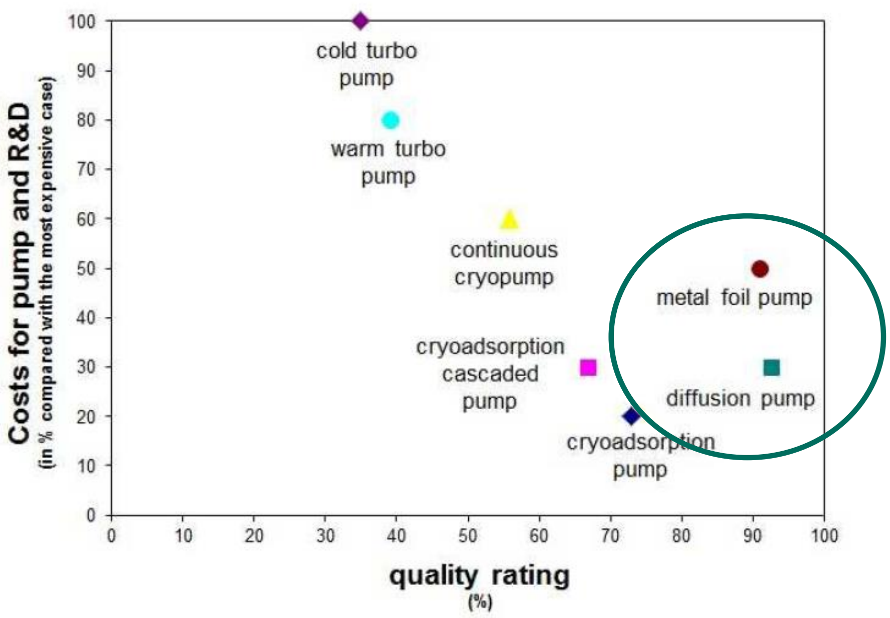


3rd step: Technical-economic examination

*[1] C. Day, T. Giegerich, IEEE Trans. Plasma Sci. **42**(4) 1058–1071 (2014).*

Primary vacuum pumping

- Vapour diffusion pumps and metal foil pumps as most promising option for primary pumping in DEMO and future fusion power plants [2]
- Main reasons: High radiation and magnetic field level tolerance; high reliability (no movable parts); no cryogenic supply needed
- Gas separation possible by the metal foil pumps; important for DIR

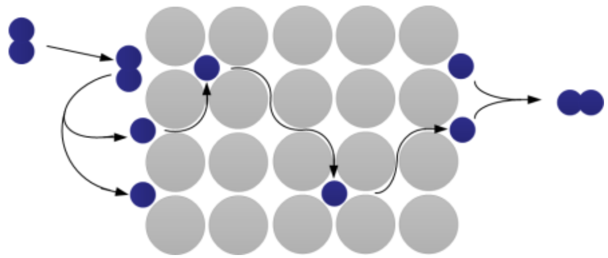


Metal foil pump + Diffusion pump most promising

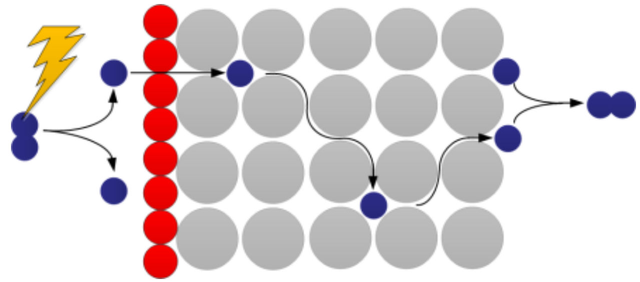
[2] T. Giegerich, Fus. Eng. Des. ***89*** *1476–1481 (2014).*

The Metal Foil Pump (MFP)

- Working principle based on *superpermeation*:



<u>Classical permeation</u>
Driving force = pressure gradient



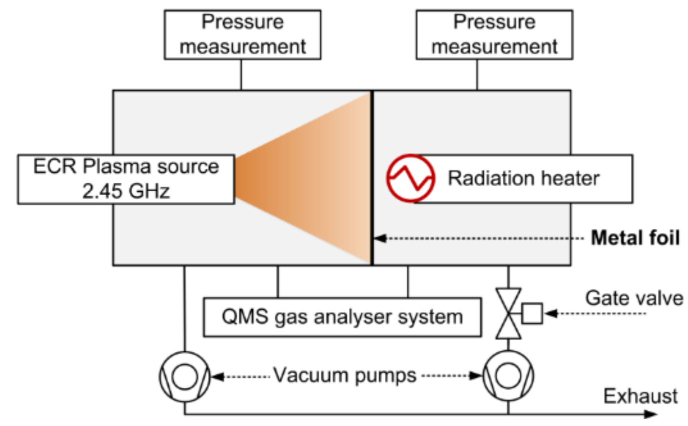
<u>Superpermeation</u>
Driving force = gradient in energetic hydrogen

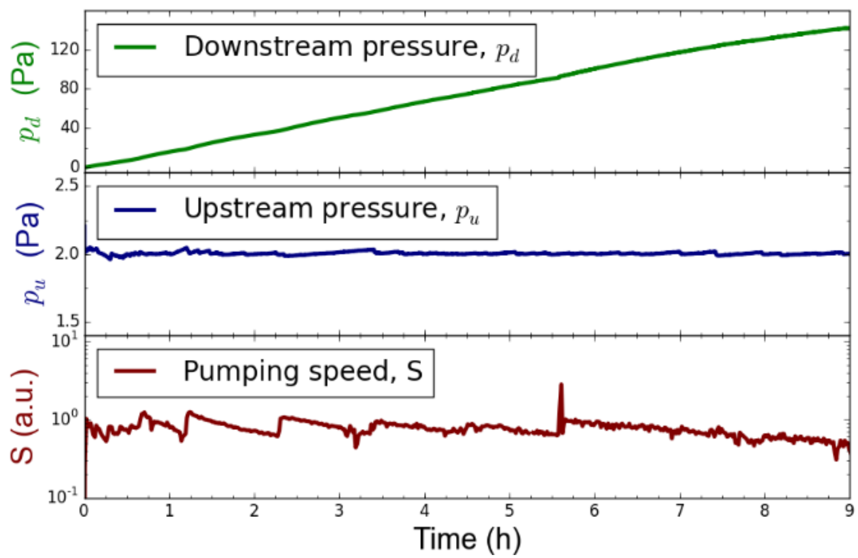
- Effect only for hydrogen species
- MFPs work only as pump for hydrogen

→ second pump for all residual gases needed (diffusion pump)

MFP development status

- A test facility (HERMES) has been set up to demonstrate superpermeability
- Experimental results have been very promising
- An upgrade has been done to achieve
  - an more DEMO-relevant pressure regime and
  - a more relevant metal foil design (tubular instead of flat)





The vapour diffusion pump

- Working principle is based on momentum exchange between the pumped gas and a working fluid
- No working fluid (mercury) backflow into the vacuum chamber (Torus)

→ Cooled baffles required

- Compact design (minimum number of components)

→ Baffles integrated in pump

- Low working fluid inventory (reduce mercury inventory)

→ External mercury boiler

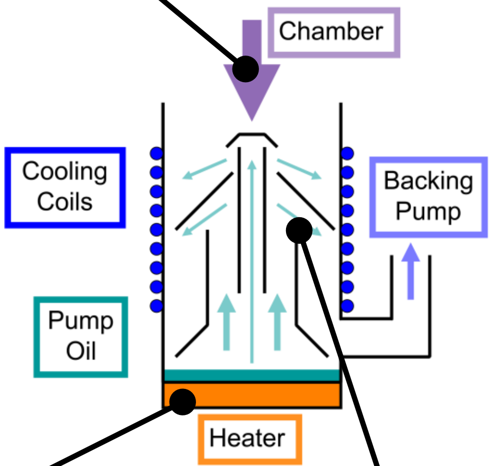
- High reliability and efficiency (economic operation)

→ Boiler heated by machine coolant, not electrically

- Easy to adapt to the required pumping speed

→ Linear pump design, scaling by length

Gas is being pumped by momentum exchange between the gas particles and the vapour jet.



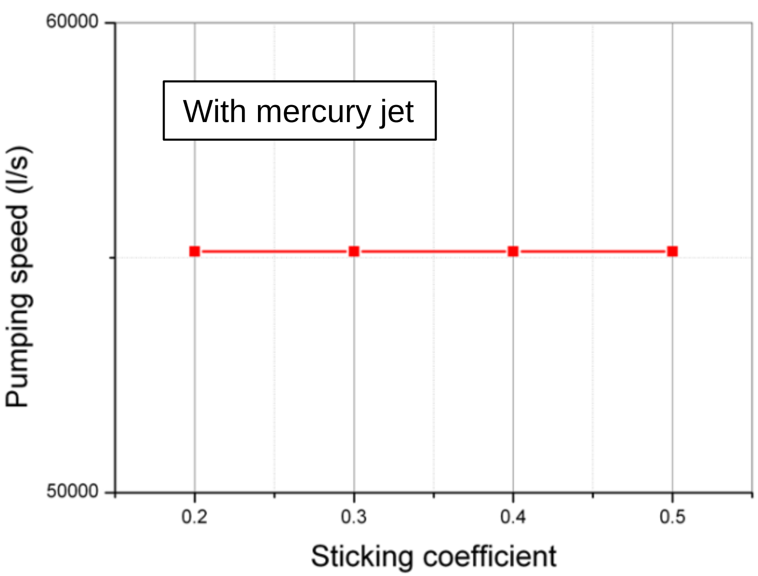
wikipedia.de: Oil diffusion pump

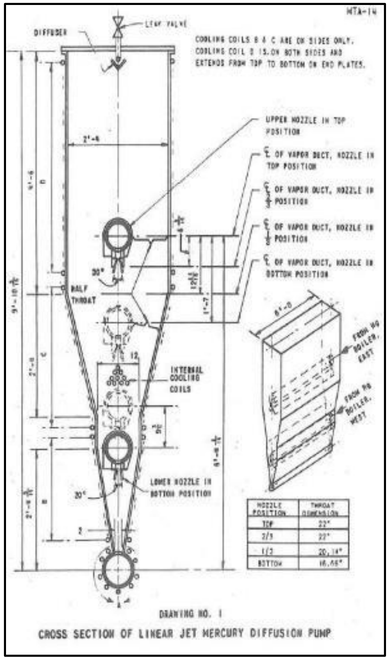
Working fluid (here: oil) is evaporated by an electric heater.

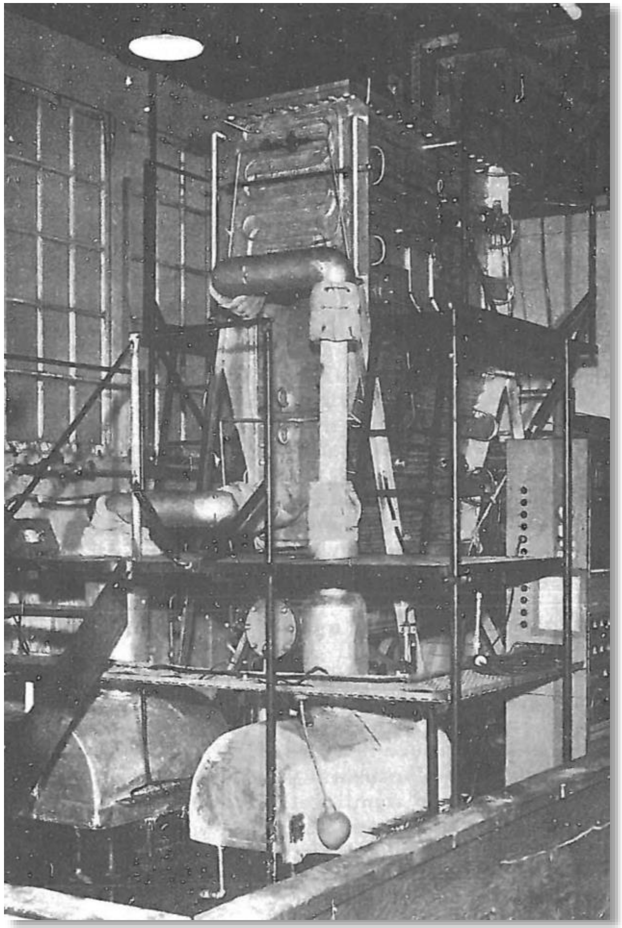
The working fluid vapour is ejected through (circular) nozzles with supersonic speed towards a cooled wall where it condenses again.

LDP development status (1)

- Only one LDP has been built so far in LLNL in 1953
- An in-house code has been developed to simulate mercury – gas interactions in LDPs to support the design activity
- This ode has been benchmarked using the 1953 test results



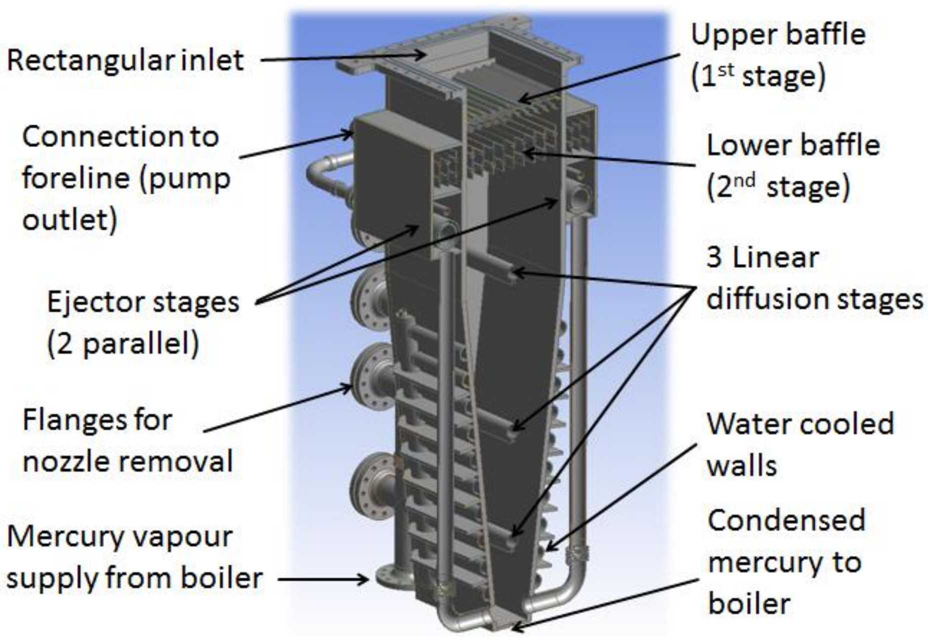


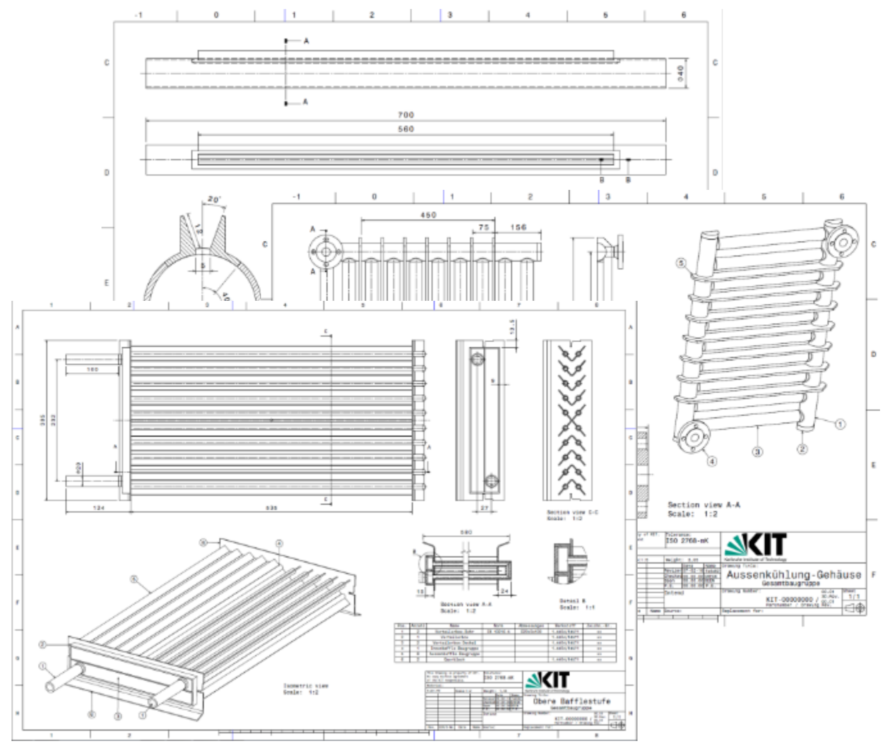


E. Lind, F. Steinhaus: *Development of a large linear jet mercury diffusion pump*, Livermore Research Laboratory, Livermore, California, US, January 1953.

LDP development status (2)

- A more modern and compact design of the 1953 pump has been developed
- Optimization by FEM methods has been done
- Safety cases have been assessed
- Manufacturing drawings for a full scale test pump currently under preparation
- The test pump will be used for code benchmarking in the THESEUS pump test facility at KIT



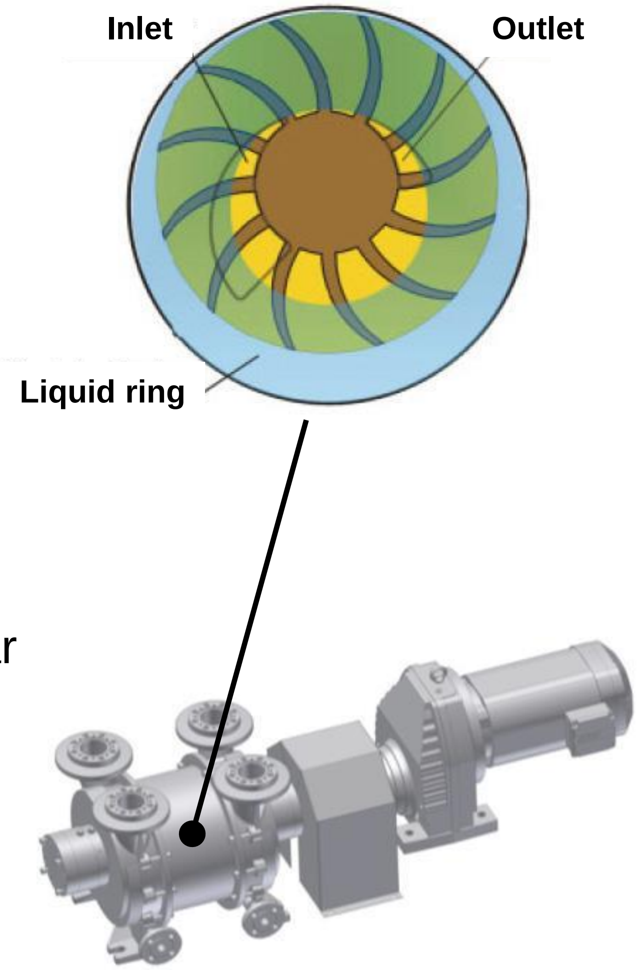


Rough vacuum pumping

- Liquid ring pumps (LRPs) as most promising option for rough vacuum pumping in fusion power plants [2]
- Working principle:
  - A rotor is eccentrically levitated in a case
  - When rotating, a liquid ring is formed
  - Gas is pushed from Inlet to Outlet
  - Volume between the blades and the liquid ring decreases → compression
  - Gas and working fluid is exhausted into a phase separator

- LRPs very robust and reliable, but ultimate pressure limited by vapour pressure of working fluid (~30 mbar for water; not tritium compatible)

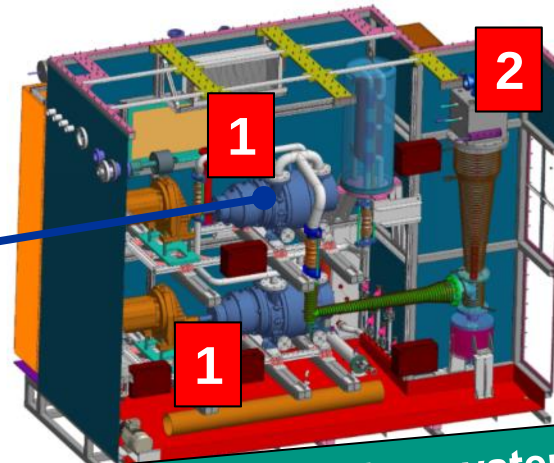
→ Limitations can be overcome by the change from water towards mercury (mercury ring pumps)



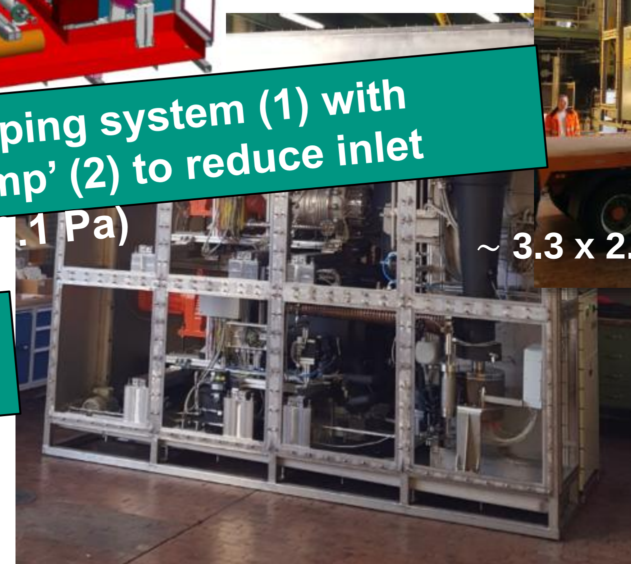
[2] T. Giegerich, Fus. Eng. Des. ***89*** *1476–1481 (2014).*

LRP development status

- A tritium compatible, DEMO-scale pump train has been developed
- Expected pump performance: Pumping speed 50 m³/h @ 1 hPa; 4 m³/s @ 0.1 Pa
- Testing under tritium foreseen at the JET fusion device in UK in 2019



From CAD to hardware (2014-2017)



2-stage pumping system (1) with 'booster pump' (2) to reduce inlet

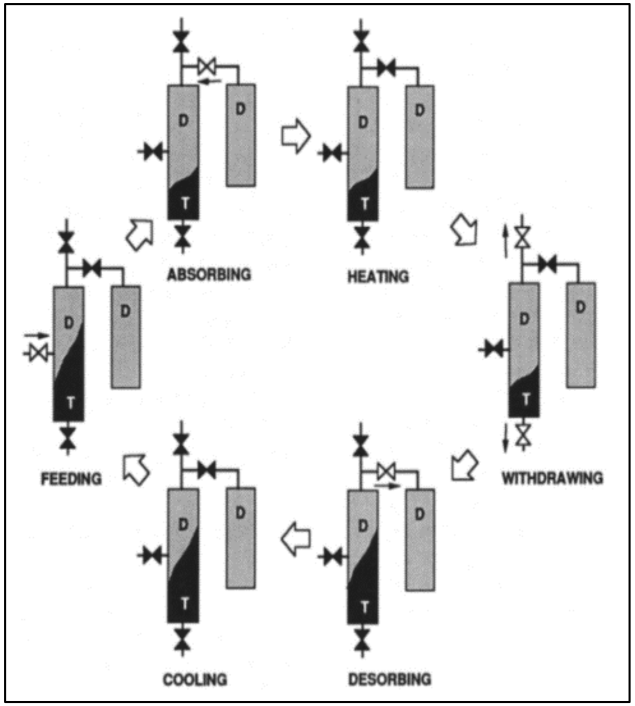
.1 Pa)

First ever mercury based continuous mechanical vacuum pump for DEMO scale

Hydrogen isotope separation – DEMO concept (1)

- Isotope separation in the DEMO fuel cycle will rely on classical, i.e. well-known methods like
  - Cryogenic destillation and/or
  - TCAP (Thermal Cycling Adsorption process) and/or
  - PSA (Pressure Swing Adsorption)

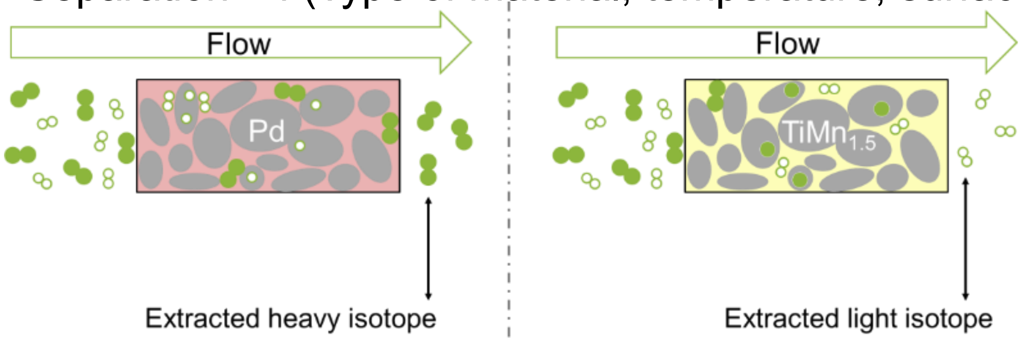
- Where only partial separation is required (e.g. protium removal or isotope re-balancing), methods based on metal-metal interactions or gaseous diffusion can be applied (*next slide*)



Hydrogen isotope separation – DEMO concept (2)

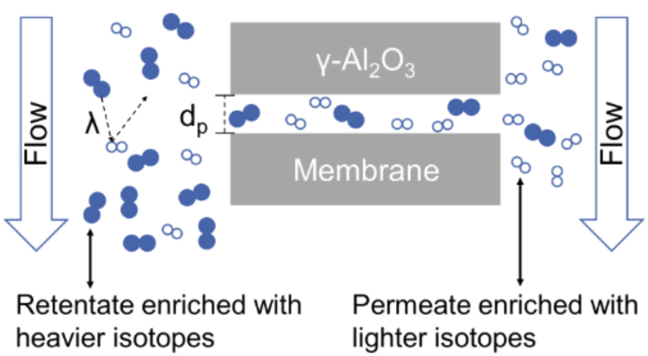
Protium Removal

Functional principle: Hydrogen-Metal Interactions
Separation = f (Type of material, temperature, surface, …)

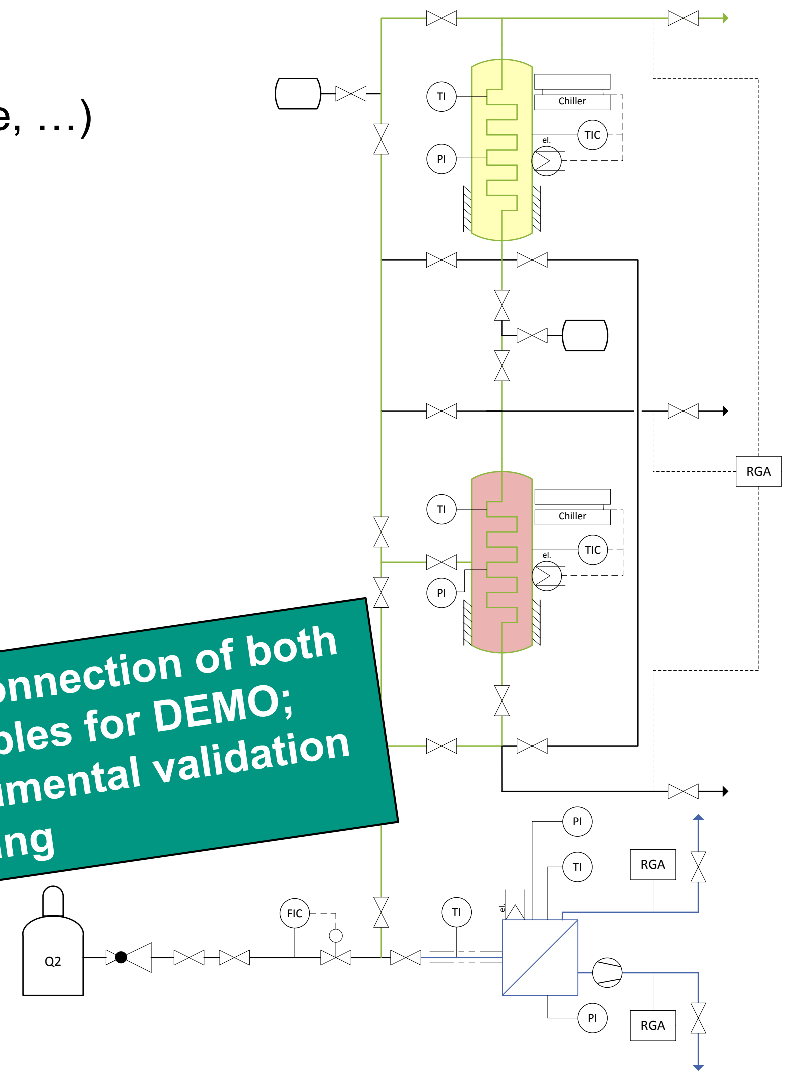


Isotope Rebalancing

Functional principle: Gaseous Diffusion ($d_p \ll \lambda$)
Separation = f (Molar masses of isotopes)



Interconnection of both principles for DEMO; experimental validation ongoing



Hydrogen isotope separation – new methods

Working principle TCAP: Alternating heating/cooling of a coated separating column

- Gas transfer due to temperature gradients
- Isotope separation due to isotope specific adsorption characteristics inside the column

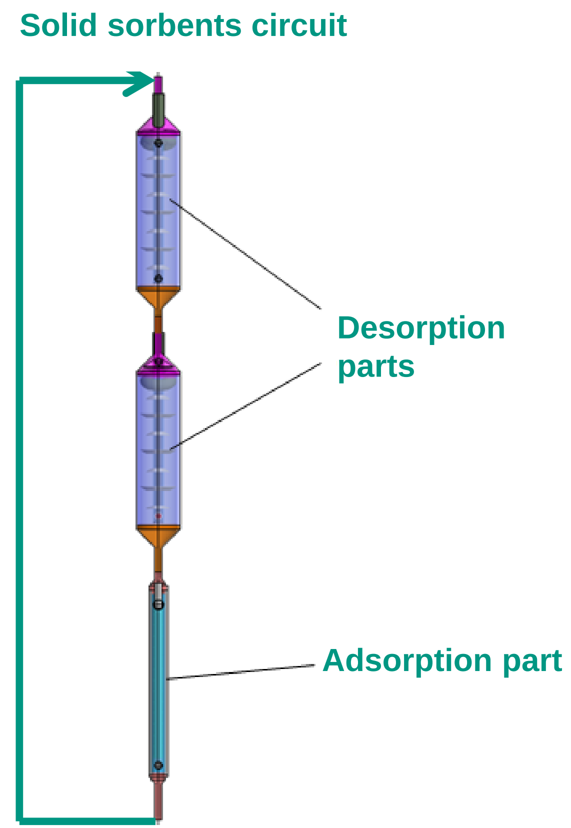
Potential problems with TCAP in DEMO scale:

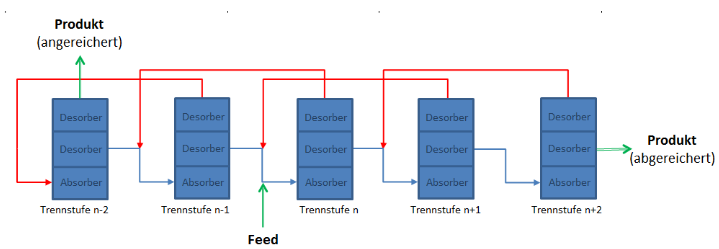
- Scailability questionable
- Very high investment (Pd sorbents)
- Very high tritium inventory (large columns)

Potential solution: The TTRAP method

- New method, based on moving sorbents and not on a moving gas
- TTRAP: *Thermal Treatment Recycling Adsorption Powder*

→ Filed for patent, full validation ongoing at KIT





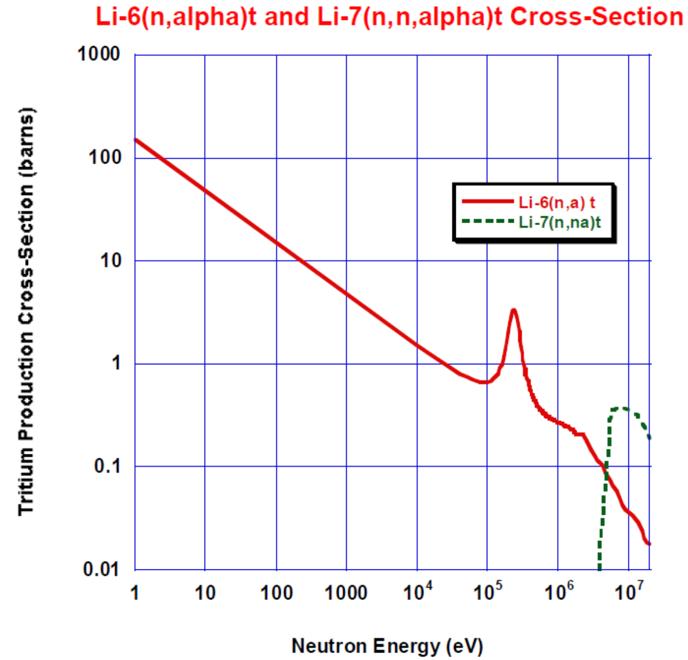
Lithium isotope separation needs for DEMO

- Tritium no primary fuel (has to be bred out of lithium inside the breeding blankets):

$$^{6}Li + n \rightarrow T + \ ^{4}He + 4{,}8\ MeV$$
$$^{7}Li + n \rightarrow T + \ ^{4}He + n' - 2{,}466\ MeV$$

- Cross section of the reaction using ^{6}Li much higher for thermal neutrons → Better to use ^{6}Li than ^{7}Li
- Natural lithium consists to 92.5% of ^{7}Li and to 7.5% of ^{6}Li → Enrichment reguired
- For fusion power plants, approx. 50 tons of pure ^{6}Li per GW_{el} will be needed
- ^{6}Li market supplied mainly by the lithium produced in US by COLEX until 1963
- No industrial-scale facility existing today that could meet the requirements for DEMO

→ **High risk for fusion**



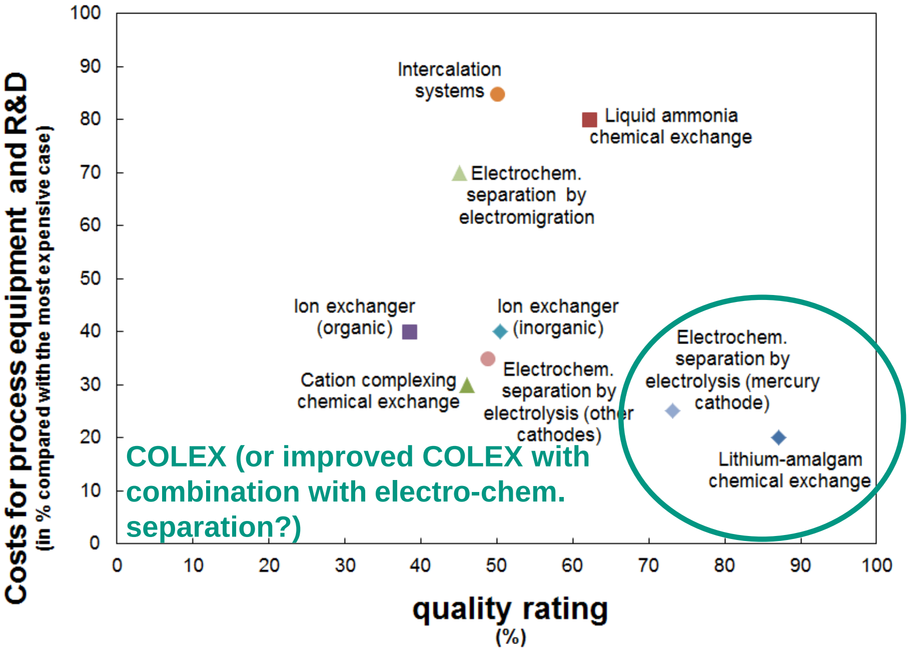
source: W. Biel, Tritium Breeding and blanket technology, Bad Honnef (2014).

Lithium isotope separation – assessment results

- In a technical-economic examination (similar as for the vacuum pumps), it was found that the 'classical' lithium-amalgam exchange (COLEX) process has the highest quality value at a low development effort
- In general, mercury based methods (chemical exchange, electrolysis) show high quality values
- Other methods have been tested in lab-scale or even technical scale but never reached high values (major reasons: bad scalability and/or high complexity, use for reprocessing of the tritiated waste from the blankets not possible)
- COLEX was used in the 50s and 60s and caused a severe environmental contamination with mercury (~11'000 t used, ~330 t lost in waste streams)

→ Work started to develop an improved and ‚clean' process that can be used to satisfy the DEMO demand

→ A mercury lab has been set up at KIT and is under commissioning



The HgLab at KIT

- General characteristics:
  - Closed room with strong ventilation and air-conditioning
  - Airlock and locker room avoids potential mercury spilling outside the lab
  - Mercury vapour monitoring in the lab air, automatic monitoring of all lab parameters
- Main purpose of the HgLab:
  - Support other experimental activities (by e.g. cleaning of components, mercury filtering and analyzing)
  - Provide environment (workspace) for experiments with mercury (e.g. enrichment experiments)
  - Develop analytic methods for mercury characterization (Agilent ICP-MS 7900 available)

www.agilent.com

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Thank you!