Neuartige Vakuumpumpkonzepte für Fusionskraftwerke

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DISSERTATION

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Novel vacuum pumping concepts for fusion power plants

by

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THESEUS

The Greek hero THESEUS, 1400 B.C., king of Athens, argonaut and Kalydonic warrior, conqueror of Minotauros and the Marathonic bull, founder of the Panathenäic and Isthmistic games, was liberated by Herakles after the abortive try to abduct Persephone, godhood of fertileness, daughter of Zeus.

Danksagung

Diese Arbeit entstand am *Institut für Technische Physik* (ITEP) des *Karlsruher Institutes für Technologie* (KIT). Bereits während des Hauptstudiums als Chemieingenieur an der Universität Karlsruhe, dem heutigem KIT, folgte ich meinem Dozenten und Betreuer dieser Arbeit, Herr Dr. Christian Day, an das damalige Forschungszentrum Karlsruhe (jetzt: KIT Campus Nord) nach Eggenstein-Leopoldshafen, wo ich alle „Hierarchiestufen“ angefangen vom HiWi über Diplomarbeiter bis hin zum Doktoranden durchlaufen durfte. Diese fünf Jahre, von 2010 bis 2015, waren für mich die lehrreichste und interessanteste Zeit in meiner Ausbildung.

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Zusammenfassung

In dieser Arbeit wird ein neues Vakuumpumpkonzept für zukünftige Fusionsreaktoren entwickelt, welches erhebliche Vorteile gegenüber vorhandenen Lösungen bietet. Die technische Umsetzung des hier vorgeschlagenen Konzepts führt zu drei neuartigen Vakuumpumpen, die ebenfalls in dieser Arbeit vorgestellt und validiert werden. Abschließend wird ein Ausblick auf laufende und noch ausstehende Aktivitäten gegeben, die zum Ziel haben in den frühen 20er Jahren einen Stand der Technik zu erreichen der es erlaubt ein detailliertes Design für das Vakuumsystem eines Fusionskraftwerks zu entwickeln.

Die Arbeit beginnt mit einer Einleitung in das Thema Fusion (Kapitel 1) und beschreibt den aktuellen Stand der Technik sowie die Herausforderungen auf dem Weg von experimentellen Anlagen hin zu stromproduzierenden Fusionskraftwerken. Eine grundlegende Einführung in das Thema Vakuumtechnik und Vakuumphysik sowie eine Beschreibung des Ziels dieser Arbeit wird in den Kapiteln 2 und 3 gegeben. In Kapitel 4 wird schließlich das neue Vakuumpumpkonzept entwickelt. Hierzu wird ein dreistufiger Ansatz aus der Produktentwicklung angewendet und beschrieben. Der Entwicklungsprozess liefert als Ergebnis eine Lösung die auf der Kombination von drei verschiedenen Pumpprinzipien basiert. Deren Funktion wurde noch nie unter fusionsrelevanten Bedingungen demonstriert, eine Validierung war daher notwendig. Die Validierung hat den Aufbau von zwei Testeinrichtungen erfordert und wird in Kapitel 5 vorgestellt. In Kapitel 6 werden schließlich die Pumpprinzipien in technische Lösungen überführt, was zur Entwicklung von drei neuartigen Vakuumpumpen geführt hat. Ein Ausblick auf laufende und noch anstehende Arbeiten sowie eine Zusammenfassung dieser Arbeit wird in den Kapiteln 7 und 8 gegeben.

Im Zuge dieser Dissertation wurde der KALPUREX-Prozess entwickelt, der durch das KIT zwischenzeitlich auch patentiert wurde. Bei diesem Prozess dient eine Metallfolienpumpe zur Auftrennung des aus dem Reaktor abgepumpten Gases in einen reinen Brennstoffgasstrom, welcher direkt in die Maschine rückgeführt wird, und in einen Restgasstrom, der reich ist an Verunreinigungen und daher in der Tritiumanlage des Fusionskraftwerks aufgereinigt werden muss. Dieses Verfahren wird als *Direct Internal Recycling* (DIR) bezeichnet und führt zu einer deutlichen Reduzierung des im Pumpsystem vorhandenen Tritiums. Beide Gasströme (reiner Brennstoff und Restgas) werden über zwei hintereinandergeschaltete Vakuumpumpen gepumpt, einer linearen Quecksilberdiffusionspumpe als Hochvakuumpumpe und eine zweistufige Quecksilberringpumpe als Vorpumpe. Der KALPUREX-Prozess beschreibt also die technische Realisierung des DIR-Konzepts mit allen zugehörigen Pumpen und der erforderlichen Infrastruktur.

Abstract

In this work, a novel vacuum pumping concept for future fusion power plants is being developed that shows strong advantages over all existing solutions. Starting with the concept development based on a purely theoretical process, the identified concept is being validated experimentally and a technical solution for its realization is finally being developed. This last step has led to the development of three novel vacuum pumps also presented in this work. Finally, an outlook on ongoing and planned activities is given. Main goal of the work presented here is the achievement of a technical readiness level high enough to start the development of a detailed vacuum system design for a fusion power plant in the early 2020s.

This work starts with an introduction on fusion (chapter 1) and describes the current state-of-the-art in vacuum pumping for fusion machines and the challenges on the way from experimental devices towards fusion power plants. An introduction on vacuum technology and vacuum physics, as well as a description of the goal of this work, is given in chapter 2 and 3, respectively. In chapter 4, a novel vacuum pumping concept suitable for fusion power plants is being developed. Therefore, a theoretical three-stage approach, coming from product development, has been applied. As result of this process, a solution that asks for the combination of three different pumping principles has been obtained. The function of these pumping principles under fusion relevant conditions has never been demonstrated; a validation was thus necessary. This proof-of-principle testing has asked for the set-up of two experimental facilities and will be presented in chapter 5. In chapter 6, technical solutions for the realization of the three pumping principles are being developed, leading to three novel vacuum pumps. An outlook on planned and ongoing activities, as well as a summary of the overall work, is given in chapters 7 and 8.

During this work, the KALPUREX process has been developed. This process has been filed for patent by the KIT intellectual property department. The KALPUREX process uses a metal foil pump for separating the reactor exhaust gases into a pure fuel flow, that is directly recycled back to the machine, and a residual gas flow, that is enriched with impurities and has thus to be processed in the tritium plant. This separating and recycling process is called Direct Internal Recycling (DIR) and leads to a strong reduction of the tritium inventory in the pumping system. Both gas flows (pure fuel and residual gas) is pumped by a two-stage pump train that uses a linear mercury diffusion pump and a two-stage mercury ring pump as fore-pump. The KALPUREX process is the technical realization of the DIR concept including all required pumps and infrastructure.

Outline

Nomenclature

Abbreviation/ Acronym	Name
AAS	Atom Adsorption Spectrometer
AGHS	Active Gas Handling System at JET in Culham, UK
ASDEX	Asymmetrisches Divertor Experiment (Tokamak at IPP Garching, Germany)
CANDU	Canada Deuterium Uranium reactor, a special type of a nuclear fission reactor
CCFE	Culham Centre for Fusion Energy in Culham, UK
CEA	Commissariat á L'énergie Atomique
DIII-D	Tokamak operated by General Atomics in San Diego, CA, US
DEMO	DEMOnstration fusion power plant; a fusion power plant currently in the pre-conceptual design phase; electricity production (approx. 500 MW) for the grid is expected in the early 2050s
DIR	Direct Internal Recycling; method developed by KIT to recycle unburned fuel close to the torus
EAF	European Activation File
EAST	Experimental Advanced Superconducting Tokamak in Hefei, China
EASY	European Activation System
ECRH	Electron Cyclotron Resonance Heating
EDA	Engineering Design Activity
EFDA	European Fusion Development Agreement (today: EUROfusion)
EPFL	École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland
EUROfusion	European Fusion Consortium (EFDA follow-up institution)
HERMES	Hydrogen Experiment for Research of Metal foils and Superpermeability
HF	High Frequency
ITEP	Institute for Technical Physics, institute at KIT
ITER	International Thermonuclear Experimental Reactor or Latin for *the way*
ITTK	Institute for Technical Thermodynamics and Refrigeration, institute at KIT
JET	Joint European Torus, Tokamak at CCFE/UK in Culham , UK
JT-60SA	Japanese Tokamak – Super Advanced, Tokamak in Naka
KATRIN	Karlsruhe Tritium-Neutrino Experiment, an experimental set-up at KIT
KIT	Karlsruhe Institute of Technology in Karlsruhe, Germany
LHD	Large Helical Device, a Stellerator in Toki, Japan

LDP	Linear Diffusion Pump
LH	Lower Hybrid
LLNL	Lawrence Livermore National Laboratory in Livermore, California, US
LRP	Liquid Ring Pump
MFC	Mass Flow Controller
MFP	Metal Foil Pump
NBI	Neutral Beam Injector
NEG	Non Evaporable Getter
NIF	National Ignition Facility at LLNL, Livermore, California, US
PAV	Permeator Against Vacuum, a tritium extraction method for liquid breeders
PDP	Plasma Driven Permeation
PPCS	Power Plant Conceptual Studies
ppm	Parts per million
PPPL	Princeton Plasma Physics Laboratory in Plainsboro, New Jersey, US
PSP	Pump Support Plant
RF	Radio Frequency
SCADA	Supervised Control And Data Acquisition system
sccm	Standard cubic centimetres per second (i.e. at 273.15 K)
slm	Standard litres per minute
stp	Standard Temperature Pressure
TBR	Tritium Breeding Ratio
TCV	Tokamak á Configuration Variable, Tokamak in Lausanne, Switzerland
TFTR	Tokamak Fusion Test Reactor, a former Tokamak at PPPL in Plainsboro, New Jersey, US
THESEUS	Test facility for vacuum pumps at KIT
TLK	Tritium Laboratory Karlsruhe, laboratory of the ITEP at KIT Karlsruhe
UTH	University of Thessaly, Volos, Greece
Tokamak	**то**роидальная **ка**мера в **ма**гнитных **к**атушках, English for *toroidal chamber with magnetic coils*, a fusion machine that contains the plasma magnetically
NSTX	National Spherical Tokamak, a Tokamak at PPPL in Plainsboro, New Jersey, US
VST	Vacuum Sieve Tray, a tritium extraction method for liquid breeders
W7-X	Wendelstein 7-X, Stellerator experiment in Greifswald, Germany

Symbol	Name / Description	Unit
S	Pumping speed	m^3/h (rough vacuum pumps) m^3/s or l/s (high vacuum pumps)
S_{id}	Ideal pumping speed	m^3/h (rough vacuum pumps) m^3/s or l/s (high vacuum pumps)
Q	Throughput	mbar l/s or Pa m^3/s
p	Pressure	Pa or mbar
w	Transmission probability	[-]
C	Conductance	m^3/h, m^3/s or l/s
C_A	Conductance of the inlet surface	m^3/h, m^3/s or l/s
E_L	Energy of liquid ring	Joule
V_L	Rotating liquid ring volume	m^3
v_L	Speed of liquid ring	m/s
ρ	Density	kg/m^3
η	Dynamic viscosity	Pa s
v_0	Mean velocity of gas molecules	m/s
L	Length	m
D	Diameter	m

1. Introduction

1.1 Why fusion energy?

The *Center for Stratec and International studies* in Washington DC expects in his *International Energy Outlook 2013* [1] the world electric energy consumption to double within 25 years, between 2000 and 2025 (Fig. 1).

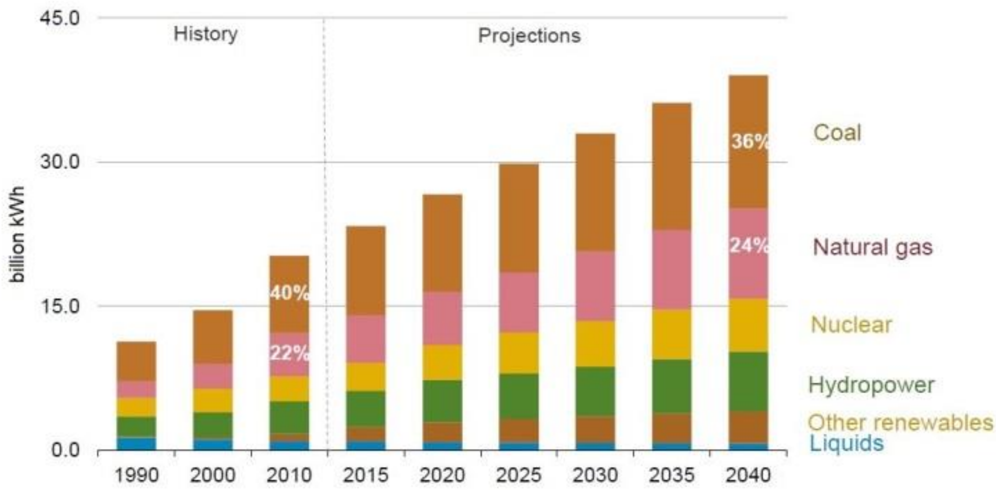


Fig. 1: World electricity consumption by fuel, outlook until 2040 [1].

In the time of a rising energy demand, natural resources and fossil fuels become short as they are not unlimited. This leads to fast rising prices on the market and thus a stronger dependency of economic growth on costs for energy. Between 2010 and 2050, the world average cross-domestic product will increase 3.6% per year and the total energy use will grow by 56%. Half of this increase is caused by India and China [1]. 80% of this enormous energy demand will be covered by burning of fossil fuel and thus causes an increase of the release of the climate changing gas carbon dioxide by 46% until 2040, finally reaching 40 billion metric tons [1]. Also here, Asian countries will be responsible for a large part of the growth. It can easily be reconstructed that these countries try to keep pollution and environmental damages low in order not to destroy their country for future generations.

The only way to keep pollution low seems the change to emission-free technologies for power generation like renewables and nuclear technology, what is expected to grow by 2.5% per year until 2040 [1]. Especially nuclear fission is the technology of prime importance for countries like China, India and South Korea, which do not see other ways to satisfy their huge industrial energy demand. Nuclear power from fission reactors has the major disadvantages that a very long-term radioactive waste (half-life up to 10^9 years) is produced.

A way out of this dilemma may be the change from fission to fusion power plants. In fusion power plants, deuterium and tritium is burnt towards non-radioactive and non-toxic helium, the ‘ash’ of a fusion power plant. As fuel for fusion reactors, deuterium (that is easily available on the market) and tritium (that is generated inside the machine out of lithium) is used. All materials used in fusion power plants are chosen such that they shall be recyclable after approx. 100 years of storage – an acceptable time period. Moreover, fusion reactors are from their physics principle intrinsically safe [2] as no energy multiplication reaction is physically possible. All these advantages are so strong that extensive research all over the world is going on. First experimental machines are running and have demonstrated that the fusion reaction – a similar reaction that powers the sun – is also possible on earth. Based on these findings, demonstration power plants (DEMO) are currently under development in a number of countries, especially in the countries with a high energy demand in the future and limited own resources (e.g. China, India, South Korea). Also in Europe, studies have been carried out that demonstrated that no principle problems for building DEMO machines are expected [3, 4].

1.2 History of nuclear fusion

On July 16th, 1945, as part of the well-known *Manhattan Project*, the first atomic bomb *The Gadget* exploded in the *Trinity Test* in *White Sands* in US and demonstrated the enormous release of energy by the fission of heavy uranium atoms. Some years later, still in the framework of the Manhattan Project, Edward Teller developed an atomic bomb based on the fusion of lighter atoms into heavier species and demonstrated it experimentally in the *Ivy Project*. On November 1st, 1952, when *Ivy Mike* exploded on the Eniwetok-Atoll, nuclear fusion was born.

To reach the enormous temperatures for the ignition of the fusion fuel mixture in these so-called ‘hydrogen bombs’, a fission bomb was necessary. Also the energy release of the device was of course not controllable. But scientists immediately recognized the possibility to use light hydrogen isotopes (deuterium and tritium) to produce helium under a huge release of energy for peaceful reasons, namely for the production of electric energy.

In contradiction to fission reactors that successfully demonstrated the possibility of electric power generation since 1954, it is not so easy to overcome the technical problems, scientists and engineers have to face while handling the enormous temperatures and machine sizes required for commercial machines. First tries to build fusion devices go back to 1956, where a group of so-called Tokamaks was built and tested at the Kurchatov Institute in Moscow to demonstrate the possibility of confining plasma and heating it up to the required temperatures under controlled conditions. At that time, no tritium was used and thus the fusion reaction could not be ignited. Even today, only two machines have ever been operated with a deuterium tritium mixture to demonstrate a controlled fusion reaction, namely the Tokamak Fusion Test Reactor (TFTR) at PPPL and the Joint European Torus (JET) at CCFE in Culham/UK.

1.3 The physics of nuclear fusion

1.3.1 The fusion reaction

In the new field of nuclear physics, extensive theoretical and experimental work was going on since the early 1940s with a large number of nuclear experimental reactors being available. As one important result, the mass defect, which is the binding energy of the nucleus divided by the number of nucleons, could be determined and plotted over the atomic mass. In such a diagram (Fig. 2), fission and fusion can be explained easily: It was found that the nucleus is very stable when the mass defect is weak (lowest binding energy per nucleon means highest stability). This can be reached by the merging of light atoms into heavier atoms (fusion) or by the cracking of heavy atoms into light atoms (fission). The atom with the lowest mass defect per nucleon (and thus the most stable one) is iron-56 (^{56}Fe).

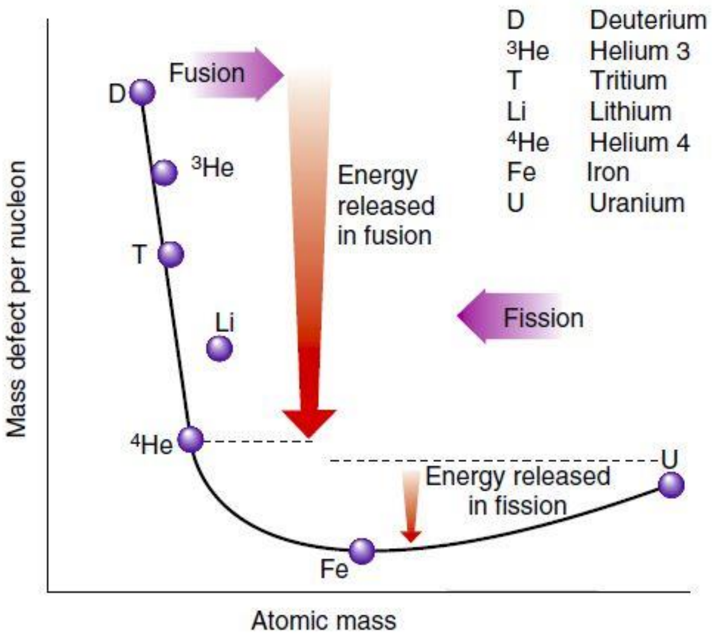


Fig. 2: Energy release from fission and fusion shown as decreasing mass defect per nucleon [5].

This work concentrates on nuclear fusion, which is the approaching of the stable state from the left side. In theory, a large number of possible fusion reactions can be found. A closer look to the energy release and the probability for such a reaction to take place leaves only some reactions as technically relevant. Tab. 1 shows some selected reactions.

Tab. 1: Possible fusion reactions and their energy release.

Number	Equation	Total energy release
(1)	D + T → ^{4}He + n	+ 17.6 MeV
(2a)	D + D → T + p	+ 4.03 MeV
(2b)	D + D → ^{3}He + n	+ 3.27 MeV
(3)	D + ^{3}He → ^{4}He + p	+ 18.3 MeV
(4)	T + T → ^{4}He + 2n	+ 11.3 MeV
(5)	^{3}He + ^{3}He → ^{4}He + 2p	+12.9 MeV
(6a)	^{3}He + T → ^{4}He + n + p	+ 12.1 MeV
(6b)	^{3}He + T → ^{4}He + D	+ 14.3 MeV
(7a)	D + ^{6}Li → 2^{4}He	+ 22.4 MeV
(7b)	D + ^{6}Li → ^{3}He + ^{4}He + n	+ 2.56 MeV
(7c)	D + ^{6}Li → ^{7}Li + p	+ 5.0 MeV
(7d)	D + ^{6}Li → ^{7}Be + n	+ 3.4 MeV
(8)	p + ^{6}Li → ^{4}He + ^{3}He	+ 4 MeV
(9)	^{3}He + ^{6}Li →2^{4}He + p	+ 16.9 MeV
(10)	P + ^{11}B → 3He	+ 8.7 MeV

A fusion reactor is only reasonable if the fuel is available in the required quantities. This excludes e.g. ^{3}He and ^{11}B as educts. For technical reasons – the temperatures in the reactor shall not be too high – the probability for a reaction (i.e. the nuclear cross-section) shall be high even at low temperatures. For the available reactions (1), (2) and (3) in Tab. 1, the cross-sections are plotted as a function of the deuteron energy (Fig. 3). The deuteron energy E can be expressed as temperature by $E = {}^3/_2 \cdot k_b \cdot T$. One can see that these reactions take place at temperatures of several million K. It is thus reasonable to select a reaction with a high cross section at relatively low temperatures; the DT fusion reaction shown in Fig. 4 is by far the most promising candidate.

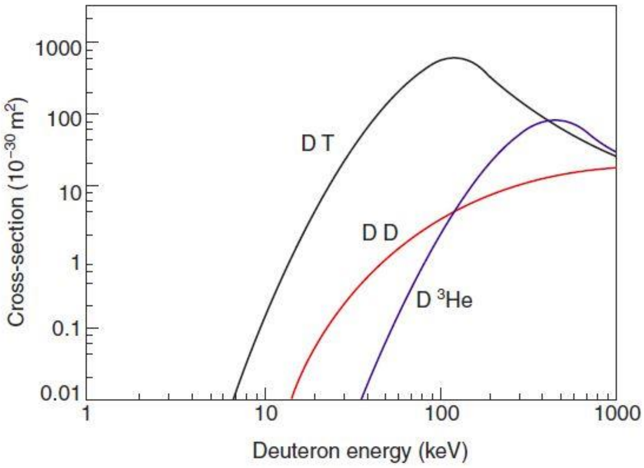


Fig. 3: Probability for a fusion reaction to take place as a function of deuteron energy for different fusion reactions [5].

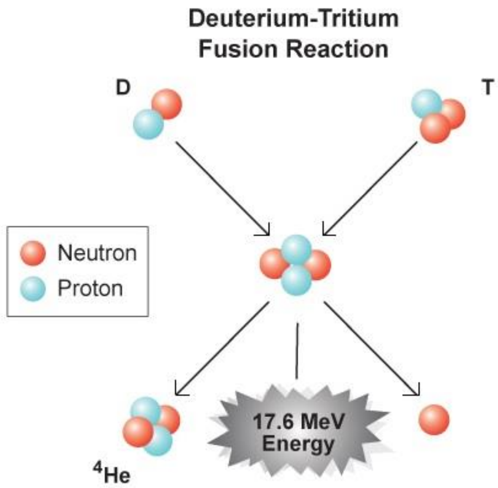


Fig. 4: The DT-fusion reaction: Deuterium and tritium is merged together under the release of Helium-4, one neutron and 17.6 MeV of energy [5].

1.3.2 Tritium breeding reactions

Main disadvantage of the DT fusion reaction is the need for tritium. Tritium is not available on earth and it decays with a half live of 12.35 years. It has thus to be bred directly inside the machine (out of lithium as described in Tab. 2 below). Furthermore, tritium is chemically highly active as it will replace protium (^{1}H) atoms in molecules and decays there into ^{3}He, what leads to a swelling effect in these substances (e.g. in oil, fat and polymers) and destroys them.

Tab. 2: Tritium breeding reactions.

Equation	**Total energy release**
$n_{slow} + {}^6Li \rightarrow {}^4He + T$	+ 4.784 MeV
$n_{fast} + {}^7Li \rightarrow T + {}^4He + n_{slow}$	- 2.467 MeV

Tritium breeding takes place in so-called breeding blankets, installed inside the vacuum vessel of the reactor (torus), close to the plasma. For self-sufficient reactor operation, a tritium breeding ratio (TBR) – describing the fraction of fuel being bred over the fuel being burned – larger than one (ideally 1.05 to 1.1) is vital. To achieve this, a large part of the torus walls have to be covered with blankets. For the blankets, different techniques can be used with solid or liquid breeder materials (i.e. lithium plus a neutron multiplier like Be or Pb) and with different cooling fluid (gas, liquid metal, water, molten salt). For neutronic reasons, to achieve a TBR larger than one, a mixture of both, Li-6 and Li-7 has to be used as both reactions have different cross-sections at different neutron energies. Hence, the fraction of Li-6 in the breeder material must be in the order of some ten percent.

1.4 Technology of fusion reactors

1.4.1 Fusion devices, fusion reactors and fusion power plants

Today, a number of fusion machines exist all over the world for the investigation of plasma physics and nuclear fusion. Only two of all these machines are, or have been, *fusion reactors* that are able to ignite the fusion reaction by handling radioactive tritium: JET and TFTR. All other machines are *fusion devices* that use only protium, deuterium or helium for plasma experiments.

The advantage for fusion devices is that no complex and expensive handling facility for tritium is needed and also tritium compatibility and safety concerns while handling (radioactive) tritium and generating neutrons plays no role. For the investigation of plasma physics – that is until now still not fully understood – fusion devices are ideal machines as plasma physics does not change significantly when using tritium plasma.

A *fusion power plant* is a fusion reactor that provides electricity to the grid using a conventional steam circuit. Fusion power plants will have to produce their own fuel (tritium self-sufficiency) and they have to produce more electricity as needed for operation – both is not necessary for fusion reactors.

1.4.2 Important subsystems for fusion reactors

Fusion reactors need a large number of technical systems to guarantee plasma operation. The most important functions that have to be fulfilled by these systems are:

- Generation of magnetic fields for plasma confinement
- Heating of the plasma to temperatures high enough for the fusion reaction to take place at a sufficiently high reaction rate
- Maintaining vacuum in the reaction chamber (torus) und processing the fuel

For providing the magnetic field to the machines, huge and very strong electromagnets are required. As the field strength is in the order of some Tesla, nowadays machines use superconducting magnets to keep losses due to the resistance of normal conducting magnets small. Superconducting magnets requires cooling to cryogenic temperatures (around 4.5 K) what immediately asks for a cryoplant and a vacuum vessel around the magnets for thermal (vacuum) insulation. The cryogenic system, needed for magnet cooling, comprises a huge helium-cryoplant and a cryogenic distribution system using vacuum insulated transfer lines and valve boxes. The cryogenic system is one of the biggest sub-systems concerning space, energy consumption (for the helium compressors) and investment costs. It is required to supply the magnet system, the cryopumps (see chapter 2.3.3) and the tritium plant (see section below). As the costs for such a system is huge and as helium – the only applicable refrigerant at a temperature level below 5 K – is expected to become short after 2020 [6], it would be an enormous advantage if the cryogenic system can be reduced or even economized. The abandonment of cryogenic pumps would be a first step, the change towards high-temperature superconducting magnets (i.e. superconducting at liquid nitrogen temperatures) a second step. The cryogenic pumps require approx. 30% of the overall cryogenic cooling capacity [7].

In fusion devices, the plasma has to be heated to start the fusion reaction. If the temperatures are too low, the reaction rate (i.e. the number of fusion reactions taking place per time interval) is too low. Heating can be done using a number of different heating methods like ion- or electron cyclotron resonance heating (ECRH), lower hybrid heating (LH) or the injection of neutral particle beams using neutral beam injectors (NBIs). From the vacuum point of view, NBI heating is interesting as it requires huge, tritium compatible vacuum pumps to generate the necessary gas transfer for neutralization: A beam of deuterium or tritium ions has to be accelerated, neutralized and finally injected into the machine. The neutralization is necessary as charged particles will not penetrate the plasma that also contains particles with the same positive charge. Therefore, the ion beam must hit a region of high gas density to be neutralized. Neutral particles will leave this region with the same energy as the ions (due to impulse exchange) in line of sight, whereas the remaining, low energetic but still charged ions will be guided by an electric field into an ion trap. Normally, NBIs require a high vacuum part to accelerate the ions without distribution with the only exception of the neutralizer region: Here, the gas density has to be high. This is the reason why NBIs require vacuum pumps with enormous pumping speeds that guarantee the required density profile along the beam line. Although not an explicit part of this work, it would be very favourable if a pumping solution can be found that is also applicable for NBIs.

Fuel processing is very important for fusion reactors. There are two parts of the fuel cycle, the *inner fuel cycle* and the *outer fuel cycle*. The inner fuel cycle is responsible for maintaining the vacuum in the plasma chamber, pumping out the exhaust gas, processing it in the so-called tritium plant and providing fresh fuel to the machine. This is necessary as the helium, produced by the fusion reaction, has to be purged out continuously of the plasma to avoid an accumulation in the core to a value of some few percent as this would lead to a strong decrease in the performance of the machine. Fig. 5 shows a simplified scheme of the fuel cycle of a fusion reactor: Deuterium, tritium and helium is pumped out of the torus by a set of vacuum pumps. In the tritium plant, the tritium is recovered, impurities removed and the hydrogen isotopes are separated and finally re-injected to the machine via storage and delivery- and fuelling and plasma control systems. Deuterium comes from outside and replaces the fraction of deuterium that has been burnt in the fusion reaction to helium. The tritium make-up comes from the breeding blankets, summarized as outer fuel cycle.

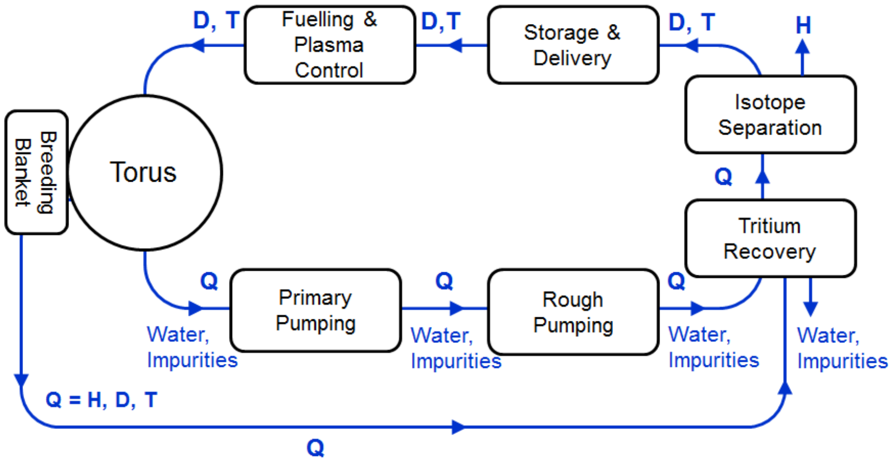


Fig. 5: Block diagram of the fusion fuel cycle.

The outer fuel cycle comprises the blankets and all required tritium extraction systems. Depending of the breeding concept chosen for the reactor (solid or liquid breeder materials; water, liquid metal or gas cooled) this are complex and huge systems. The fusion reactors ITER (see chapter 1.5.1) will be supplied with tritium extracted from heavy water fission reactors (e.g. CANDU reactors that bred tritium with a rate of approx. 200 g per GW and full power year [8]) and will only have a very small outer fuel cycle for experimental purposes (i.e. demonstration of the breeding concept). The first fusion power plant that produces electricity to the grid, DEMO, will have to demonstrate self-sufficiency and thus requires a full-scale outer fuel cycle (factor 10^4 in throughput compared to ITER).

This work will focus only on the inner fuel cycle. However, a large number of high-throughput vacuum pumps may be required in future to extract the tritium from liquid breeder materials. It would be good if the pumping solution developed for the inner fuel cycle can also be used here to keep the whole system as simple as possible.

1.5 Nuclear fusion – Present and Future

1.5.1 State-of-the art in fusion

Today, a large number of fusion machines exist all over the world. They are especially used for the investigation of plasma physics. Only two of these machines are fusion reactors: TFTR and JET. The Tokamak Fusion Test Reactor (TFTR) at the Princeton Plasma Physics Lab (PPPL) in Plainsboro, US was operated between 1982 and 1997. The Joint European Torus (JET, Fig. 6) that is in operation since 1983 at the Culham Centre for Fusion Energy (CCFE) in Culham, UK, is up to now the largest fusion machine existing.

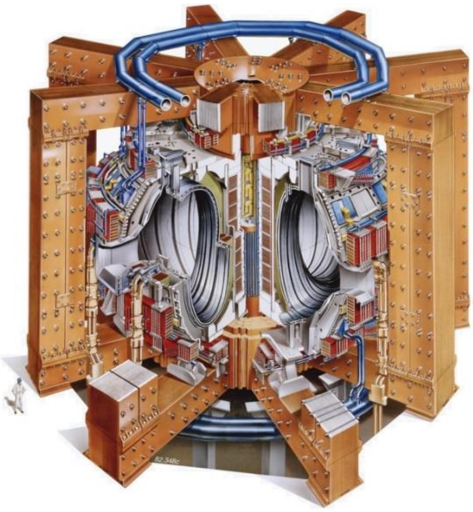


Fig. 6: Cut-view of the JET Tokamak at CCFE/UK. The small person in the lower left corner shows the dimensions of the machine. (Photo: EFDA/JET)

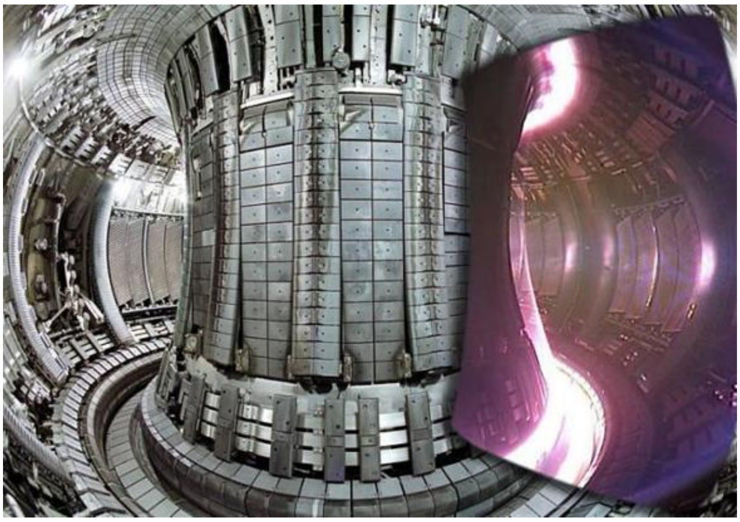


Fig. 7: Photograph of the JET torus during maintenance (left part) and during plasma operation (right). (Photo: EFDA/JET)

JET holds the world record in fusion power (16 MW at 23 MW plasma heating) achieved in 1997. This gives a Q-value (expressing the fraction of fusion power over the plasma heating power) of 0.7 [9]. For 2017, a new deuterium-tritium experiment (DTE2) is planned in JET [10]. This will be the first tritium campaign after more than 10 years operation as fusion device with only hydrogen and helium plasmas.

Another fusion reactor is currently under construction: ITER, the *International Thermonuclear Experimental Reactor* (or the Latin word for 'the way'). This machine is an international project located in Cadarache, France and will be much larger as JET. The machine is designed to reach Q = 10, demonstrating the first time that fusion reactors can reach – and even exceed – the break-even point of Q = 1, where the same amount of energy is needed for plasma heating than generated by the fusion reaction. Deuterium/Tritium plasma operation in ITER is expected not before the late 2020's. A cut-view of ITER with its major components is shown in Fig. 8. The height of the machine will be approx. 30 m with a total mass of more than 28.000 tons.

In Germany, W7-X has been commissioned recently. W7-X is a fusion device and will not handle tritium. Its first plasma has been achieved in December 2015.

Other important fusion devices for fusion research are ASDEX Upgrade (Garching, Germany), JT60-SA (Naka, Japan), TCV (Lausanne, Switzerland), DIII-D (San Diego, USA), WEST (Cadarache, France), EAST (Heifei, China), MAST (Culham, UK), KSTAR (Daejeon, South Korea), SST-1 (Gandhinagar, India), NSTX

(Princeton, USA) and LHD (Toki, Japan). Some of these machines are not operational at the moment due to major upgrades that are currently being done.

Up to now, no fusion power plant is existing or under construction. In countries like China, India and Korea, developments in nuclear fusion power plants are strongly pushed as it is seen as necessary for future economic growth. Korea has recently passed a law that forces the country to build fusion power plants in near future [11]. Also Europe has presented a 'roadmap to fusion energy' that presents a plan to fusion energy by around 2050 [12].

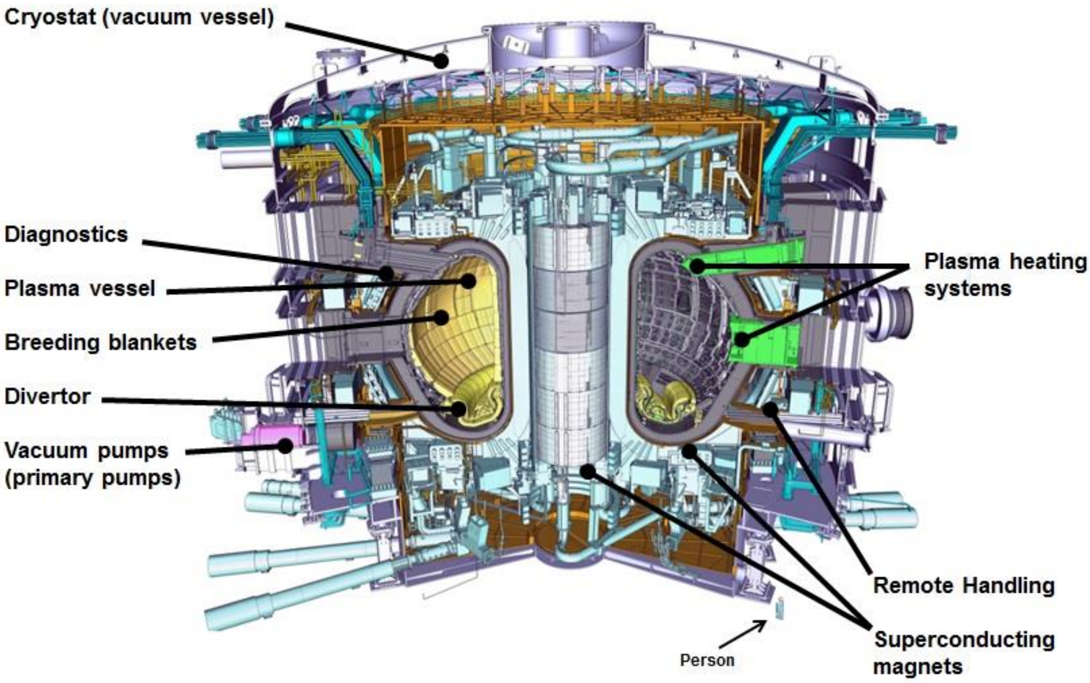


Fig. 8: Cut-view of the ITER fusion reactor. (www.iter.org)

1.5.2 Technical challenges on the way to a fusion power plant

The step from fusion devices to a fusion power plant is huge. Tokamaks allow only a pulsed plasma operation. An economically attractive fusion power plant requires a steady-state (or at least a long pulse) plasma operation to guarantee a continuous power output to the grid. Nowadays machines have demonstrated only plasma pulse lengths up to 6 minutes (world record by Tore Supra, today WEST); the maximum pulse length in JET is approx. 30 seconds), so a lot of work is still required here.

The neutronic radiation under reactor conditions is at least one order of magnitude higher than in ITER. It has to be ensured that all materials can tolerate the radiation to ensure that the resulting damage leads to acceptable degradation of the material properties. New materials, joining methods and cooling concepts have to be developed, tested and qualified to handle the heat loads on the components located close to the plasma. The neutronic radiation generated by the fusion reaction will lead to an activation of in-vessel components what has to be considered during maintenance periods: Personal access or hands-on work will not be allowed and thus requires remote handling- and maintenance systems for all in-vessel components. All systems and components used in a power plant have to be reliable enough to keep unplanned shut-down times as low as possible.

A fusion power plant has to be a self-sufficient machine that can breed its own tritium. The means that the outer fuel cycle incl. all tritium breeding and -extraction systems is needed. Until now, none of these systems have ever been build and tested.

In view of magnet- and plasma heating systems, very powerful, reliable components have to be used and operated continuously. All these systems will be larger and more complex, using in some areas – e.g. in the field of high temperature superconductors – new materials than present systems what asks for a long-term development effort.

Last but not least, a fusion power plant will be a nuclear facility asking for a complex licencing procedure. To make this possible, one issue will be the tritium inventory in the machine. A scaling from ITER towards a fusion power plant would most probably lead to an inventory that is much more that can be tolerated by the regulator. New solutions have thus to be developed that minimizes the amount of radioactive tritium in the machine.

As the step from present fusion reactors like JET and ITER towards a fusion power plant would be too large, an intermediate step has been introduced: DEMO, a demonstration power plant. After ITER has demonstrated the possibility to overcome the break-even point and to breed tritium, DEMO shall demonstrate tritium self-sufficiency and the generation of electricity for the grid with an acceptable availability and reliability of the machine. Tab. 3 compares different criteria for fusion devices, fusion reactors (ITER as most advanced example), DEMO and fusion power plants.

Tab. 3: Comparison of different criterion for fusion devices, fusion reactors, DEMO and fusion power plants.

	Fusion devices	**Fusion reactor (ITER)**	**Demonstration fusion power plant (DEMO)**	**Fusion power plants**
Machine size	Small	Large	Very large	Very large
Pulse time (Tokamak)	Up to seconds	Seconds	Hours	Hours or steady-state
Neutronic radiation to in-vessel components	Neglectably small	Medium	Large	Very large
Magnet system	Superconducting magnets or normal conducting copper coils	Large superconducting magnets	Large superconducting magnets	Large superconducting magnets
Reliability	Not very important	Low (≤40%)	High	Very high
Investment costs	Relatively low	Very high	Very high	High
Plasma heating	Moderate, only for short pulses	Strong, several methods used	Very strong, only some methods selected	Very strong, selected methods, steady-state
Remote maintenance	Not required	Required	Required	Required
Inner fuel cycle	Not required	Required; low throughput	Required, high throughput	Required, very high throughput
Outer fuel cycle	Not required	Not required, fuel comes from abroad	Required	Required

2. Vacuum physics and technology

2.1 Introduction to vacuum physics

The pressure p in a system is defined as force executed from particles perpendicular to a defined surface. If the pressure is below atmosphere, this condition is commonly described as vacuum. Vacuum systems of fusion machines are operated in a wide range of vacuum conditions, from 10^5 Pa down to 10^{-5} Pa. They are thus covering most of the vacuum regimes listed in Tab. 4, from rough vacuum to UHV.

Tab. 4: Pressure regimes in vacuum [13].

Vacuum regime	Pressure range
Rough vacuum	$10^5 – 10^2$ Pa
Fine vacuum	$10^2 – 10^{-1}$
High vacuum (HV)	$10^{-1} – 10^{-5}$ Pa
Ultra high vacuum (UHV)	$10^{-5} – 10^{-9}$ Pa
Extreme high vacuum (XHV)	$< 10^{-9}$

An important number in vacuum technology is the gas throughput Q, typically given as volumetric flow (pV-flow) in the unities mbar l/s or Pa m³/s at a reference temperature of 273.15 K. Using the ideal gas law allows the calculation of the mass flow for a given gas. Knowing Q and p, the pumping speed S of a vacuum pump can be calculated by

$$S = \frac{Q}{p}. \qquad (2.1)$$

Typical unities for S in the rough- and fine vacuum are m³/h, at lower pressure ranges it is normally given in l/s or m³/s.

If a pump is connected via a duct to a vessel, the gas particles in the vessel have to reach the inlet of the pump before being pumped. Depending on the geometry of the duct, not all particles will reach the pump inlet; a fraction of particles will be scattered back. The fraction of particles passing the pipe, compared with the particles entering the pipe, is given in a dimensionless number, the transmission probability w (between 0 and unity). Hence, the pumping speed S that can be provided to the vacuum system via a duct is given by

$$S = w \cdot S_{id}, \qquad (2.2)$$

where S_{id} is the ideal pumping speed of a pump without duct. The transmission probability plays a major role especially at very low pressures, where the well-known Navier-Stokes equations are not valid any more as the particle density is so low that only the interaction between particles and the surrounding walls (not between the particles itself) dominates the flow regime. In this so-called molecular flow regime, the transmission probability can be calculated using Monte-Carlo methods that track a large number of particles and simulate their interaction.

Knowing the transmission probability w, the conductance C of a duct (or any geometry) can be calculated by

$$C = w \cdot C_A, \qquad (2.3)$$

where C_A is the conductance of the inlet surface. The conductance has the same unit as the pumping speed and denotes a maximum possible value that can be provided via a given surface.

2.2 Introduction to vacuum generation

Vacuum is generated by one or more vacuum pumps connected in series. The performance of every vacuum pump is characterized by (i) a pumping speed S and throughput Q at a given inlet pressure and (ii) the ultimate pressure (the lowest achievable pressure at 0 throughput). If a vacuum of some Pa or below is required, a combination of pumps has to be used comprising a primary (or high vacuum) pump that works at the higher vacuum and a roughing (or backing) pump that works at a lower vacuum and compresses against atmospheric pressure, providing the fore-vacuum for the primary pump. Such a 'pump train' is necessary as one single pump alone cannot achieve a sufficiently high compression (outlet pressure divided by inlet pressure). For primary pumps, the maximum allowed inlet pressure and the foreline resistance (the maximum allowed pressure at pump outlet) are additional important characteristics that have to be considered.

The choice of the ideal pump or pump train for a pumping task depends on

- the required pressure in the system,
- the gas that has to be pumped (gas type, neutral or corrosive, condensing or not),
- cleanliness conditions (e.g. oil-free requirement),
- operational issues (e.g. special maintenance requirements, continuous pumping needed),
- space and geometrical requirements (especially for primary pumps when installed in-vessel),
- etc.

If two or more vacuum pumps have to be combined to a pump train, it has to be ensured that (i) the expected throughput can be handled by all pumps and that (ii) at this throughput the roughing pump operates at an inlet pressure that can be tolerated as foreline pressure by the primary pump. The expected throughput Q is crucial for the design of each vacuum system where a pressure p has to be reached and kept constant.

On the market, a large number of different vacuum pumps are available. All pumps can be classified according their working principle (Fig. 9). Vacuum pumps are either gas binding- or gas transfer pumps. Pumps to be used in the XHV pressure regime are typically gas binding pumps that are activated once UHV conditions are achieved using another pump train. Gas binding pumps do not allow gas processing and can only be operated until they are 'full'; then they have to be regenerated or replaced, depending on the pump type. The following section presents a choice of the most important vacuum pumps.

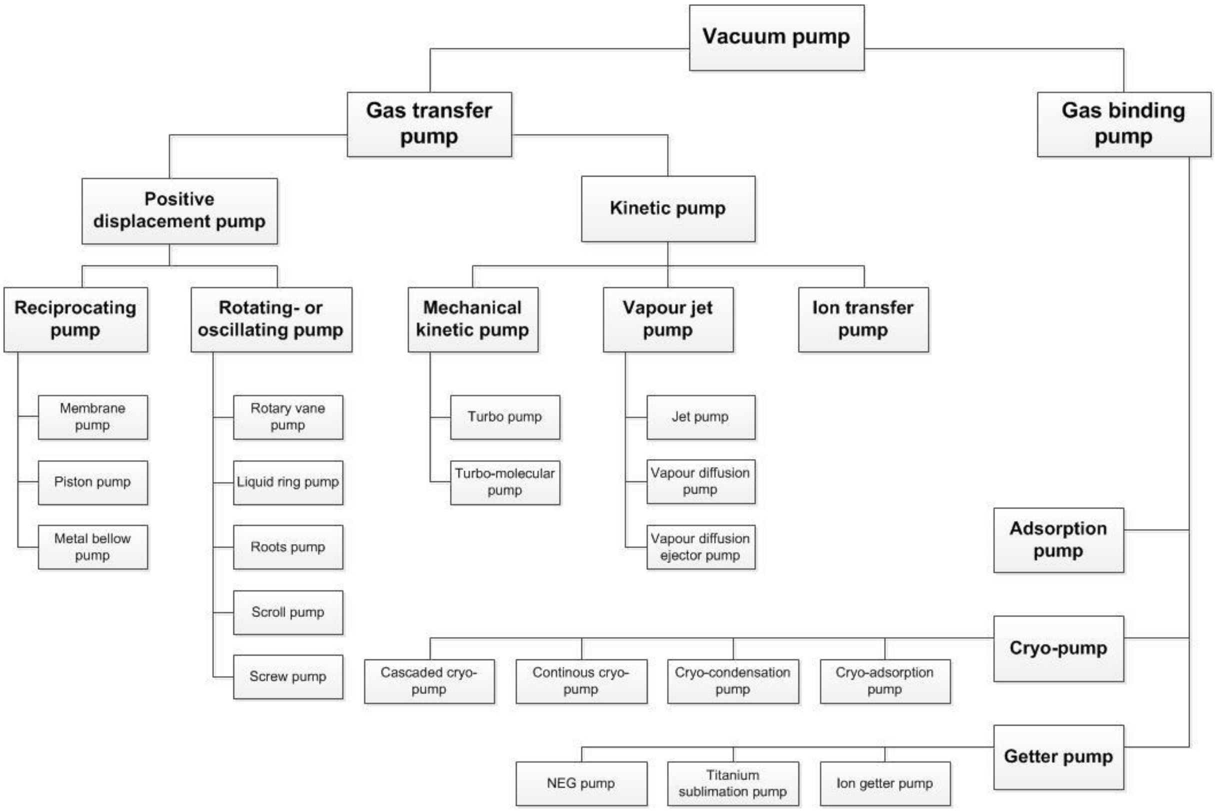


Fig. 9: The vacuum pump tree.

Positive displacement pumps

- Membrane-, metal bellow- or piston pumps

In these pumps, a membrane, a metal bellow or a piston reciprocates in a cylindrical volume and displaces the gas volume depending on the oscillating frequency. Such pumps need inlet and outlet valves and are available from small to very large sizes. The dead volume of the valves leads to an achievable pressure in the fine vacuum range what allows the use of these pumps only as roughing pump. Due to the oscillation, a complex mechanic (gear box) is needed and the maintenance requirements are high. Membrane- and metal bellow pumps (Fig. 10) are hermetically tight what makes them to dry (i.e. oil-free) pumps.

- Screw pumps

A screw pump is a positive displacement pump that uses two fast (some 1000 rpm) rotating screws (Fig. 11) to transport the gas along the screw axis through the pump. Between the two screws, a cavity is formed whose volume decreases along the screw axis which leads to a compression of the gas. A cooling fluid is necessary to carry off the compression heat produced during operation. Large-sized pumps have to employ an effective gas cooling management in order to limit exhaust temperatures. These pumps are available in sizes of some hundred m^3/h and they are normally operated without oil in the vacuum chamber (dry pumps). Screw pumps can compress to atmosphere and reach an ultimate pressure of 0.1 Pa, depending on the gas species that is being pumped.

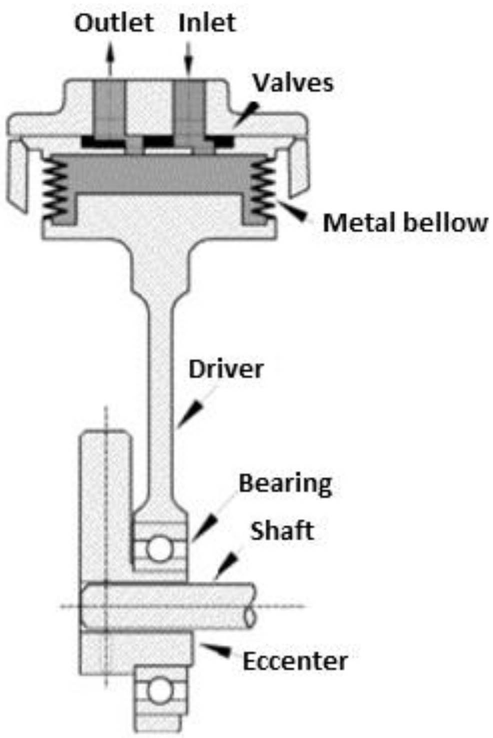


Fig. 10: Schematic view of a metal bellows pump. (Taken from Senior Flexonics company brochure)

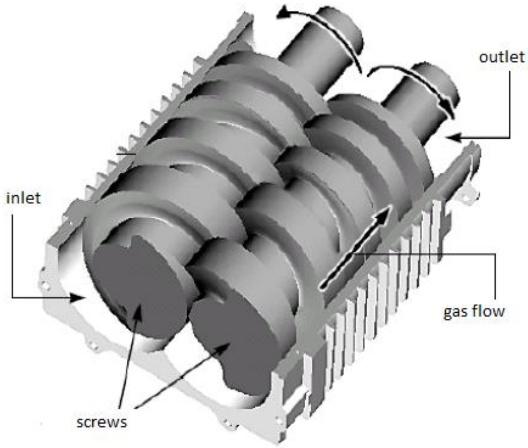


Fig. 11: Principle of a screw pump (taken from Leybold company brochure).

- Rotary vane pumps

Rotary vane pumps are the 'workhorses' everywhere, where a not very clean rough- or fine vacuum is needed. A typical application is as backing pump for turbo- or diffusion pumps, used for insulation vacuum pumping. In these pumps, a rotor is placed in a cavity whose centres are offset. When rotating, the vanes are sliding in the cavity and separate it into inlet chamber, compression chamber and outlet chamber (Fig. 12). The vanes have to be tightened against the cavity. In conventional wet pumps, this is done by oil which has also the function of a lubricant. Such pumps are available as medium-size pumps reaching ultimate pressures in the fine vacuum region. Small pumps are also available as dry pump but only with ultimate pressures of the order of 100 hPa. These pumps become very hot during operation and the pumping performance for hydrogen and the lifetime is relatively poor and the maintenance requirements are high.

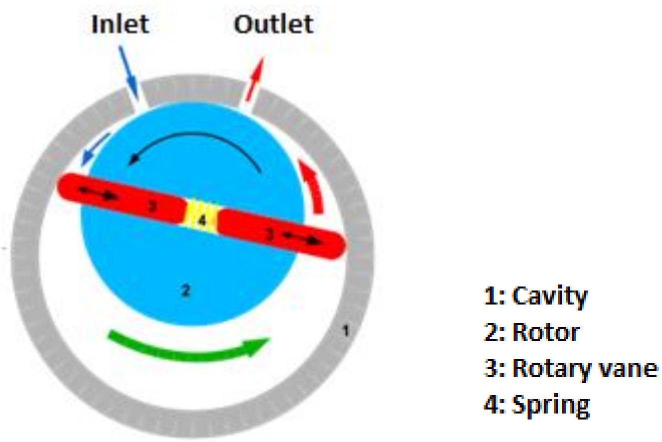


Fig. 12: Schematic view of a rotary vane pump. (https://en.wikipedia.org/wiki/Rotary_vane_pump)

- Roots pumps

Roots pumps consist of a pair of matching lobes that are rotating in a casing on rolling contact synchronized by a gear pair (Fig. 13). The gas is trapped in pockets and carried from the intake to the outlet side. The compression takes place at the outlet of the pump and not inside because the volume of the pockets does not change while the gas is carried through the pump. Due to the non-contact operation of the lobes (only a small gap remains between the two pistons and towards the pump), the pistons can rotate at high speed and, high pumping speeds (several 1000 m^3/h) can thus be achieved. At high pressures, the pump heats up strongly and a high gas backflow through the gas takes place, leading to poor compression. Roots pumps are therefore typical pumps for the intermediate pressure regime between e.g. a rotary vane pump and another high vacuum pump. Normally they are turned on at a foreline pressure of less than 1hPa and they pump down to 10^{-2} Pa.

- Scroll pumps

Scroll pumps use two interleaving scrolls to transport the gas. Normally one of the scrolls is fixed while the other orbits via a crankshaft eccentrically inside the other one (Fig. 14). Thereby, the gas is taken at the periphery of the scrolls and progressively pushed with compression towards the centre from where it is finally ejected through a discharge port. In the last decade the scroll pump has become very popular in general vacuum applications as backing pump of turbomolecular drag pumps. These pumps are typically of small pumping speed and have a feedthrough design with polymer bearings. There is only one manufacturer (EUMECA; formerly Normetex) that produces very large all-metal pumps in which the pumping area is totally isolated from the lubricated parts of the pump and the external atmosphere via a bellow. These large scroll pumps (with pumping speeds of the order 1000 m^3/h) have to be used with membrane, metal bellow or piston pumps as backing pump. The EUMECA scroll pumps are very bulky and contain a few 100 kg of oil. An intense characterisation and test programme was conducted in the 1990s at KIT [14]. It was found that scroll pumps show a strong isotopic effect (protium being pumped significantly worse than deuterium or other heavier gases) which was attributed to back diffusion along the helical flow paths of the adjacent channels.

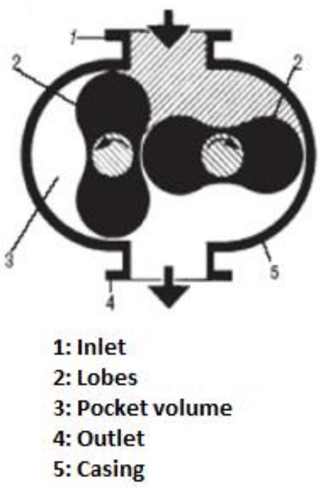


Fig. 13: Schematic view of a roots pump.

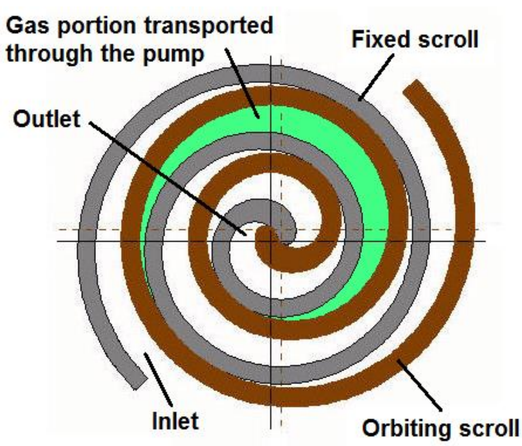


Fig. 14: Mechanism of a scroll pump.

- Liquid ring pumps

Liquid ring pumps are positive displacement pumps where a liquid ring takes over the function of a piston that compresses the gas and removes the compression heat. A wheel is placed in a cavity whose centres is offset and forms eccentricity. If the cavity is filled to some parts with a working fluid and the wheel is turned, a liquid ring is formed (Fig. 15). The gas volume between the wheel blades is compressed while pushing it from the inlet port towards the discharge port. Due to the intense contact between gas and fluid, the working fluid completely absorbs the compression heat so that the temperature of the pumped gas hardly rises and the compression can be considered quasi-isothermal. These pumps are very reliable and can pump also dust, condensing vapours and any kind of gas compatible with the working fluid. Liquid ring pumps are available in very large sizes up to more than 10.000 m^3/h. They need a phase separator at the outlet side to separate the working fluid from the exhaust gas. The fluid (typically water) is recycled into the pump and has to be cooled because of the compression heat produced by the pump. Normally, the ultimate pressure is limited by the vapour pressure of the working fluid which is in the 10^3 Pa-region for water. However, liquid ring pumps can use any fluids compatible with the process.

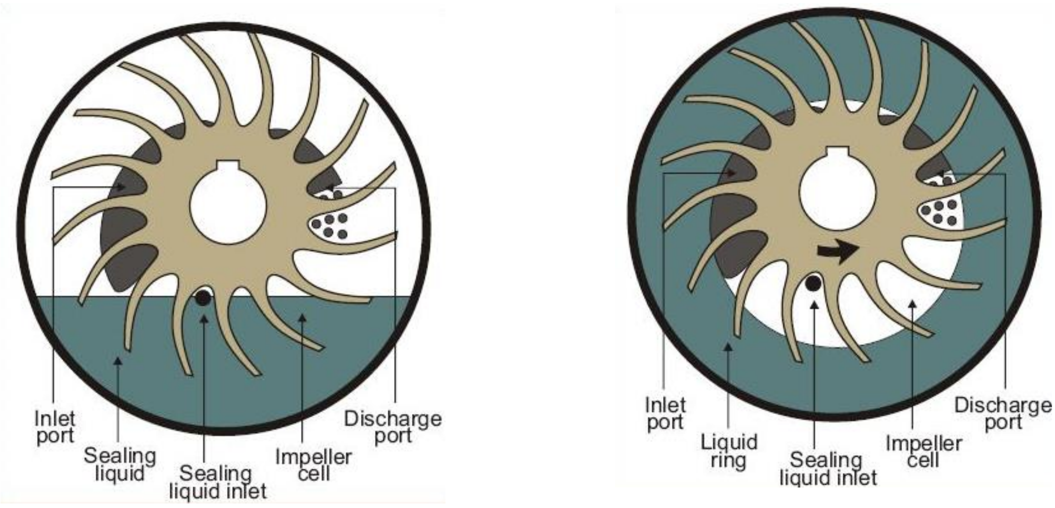


Fig. 15: Cut-view of a liquid ring pump during stand-by (left) and operation (right). (www.dekkervacuum.com)

Kinetic vacuum pumps

- Turbo or Turbomolecular pumps

The pumping effect of turbo pumps is based on an intense impulse exchange between the pumped gas particles and fast rotating rotor blades. Each rotor is followed by a (non-moving) stator. For a good pumping performance, the rotational speed of the rotors must be in the range of the thermal speed of the pumped gas particles, which is especially for light gases (like hydrogen) some hundred or even thousand m/s. This leads to high mechanical forces to the rotor blades that are rotating at several hundred Hertz and limits the available pumping speed to approx. 4 m^3/s (250 mm inlet diameter) per pump. For reaching a high compression, the pump must contain approx. 20 pairs of rotors and stators. Turbo pumps are high vacuum pumps and can only be operated at pressures below 10 Pa, otherwise the heat load to the rotors and the mechanical load to the electric drive gets too high. Higher foreline pressures (> 100 Pa) can be reached if a molecular drag stage (i.e. two parallel plates or concentric pipes with a very small gap in between) is included, leading to a so-called turbomolecular pump. These pumps have become very popular as high vacuum pumps because their operation is very simple and a vacuum below 10^{-6} Pa can be reached. In the last years, efforts have been undertaken to develop a 'cold' turbo pump, operating at cryogenic (e.g. 77 K) temperatures [15]. In this case, the gas density is being increased what should lead to a higher pumping speed at given pump size. Unfortunately, this development was never successful, mainly for two reasons: Firstly, the magnetic levitation at this low temperature never worked probably and, secondly, it could be shown that the thermal-creep effect, that leads to a flow against the pumping direction due to a thermal gradient, overcompensates the advantage of the low operational temperature [16].

- Jet- or ejector pumps

A jet- or injector pump uses the Venturi-effect of a nozzle to convert the energy of an evaporated working fluid to velocity energy which creates a low pressure zone that draws in and entrains the pumped gas. After passing the injector, the mixed fluid (pumped gas + working fluid vapour) expands and the velocity is reduced again which results in the recompression of the mixed fluids by converting kinetic energy back into pressure. Downstream the ejector, the working fluid is typically condensed and removed out of the gas mix. In laboratory scale, mercury ejector pumps have been used in the past as primary pumps to generate a fine vacuum. Today, most roughing pumps can reach this pressure regime without requiring a cooling infrastructure and without producing working fluid vapour contamination is the system. For rough vacuum generation in e.g. the condenser of power plants or in chemical plants, steam ejector pumps are often used.

- Vapour diffusion pumps

Vapour diffusion pumps are the oldest high vacuum pumps, developed at the beginning of the last century (1915) by Gaede [17]. They can operate under HV until UHV conditions and have been commonly used before turbo pumps have entered the market. The working principle is based on the evaporation of a working fluid (initially mercury; nowadays synthetic oils), as illustrated in Fig. 16. The vapour is being ejected through circular nozzles with supersonic speed towards the cooled wall of the pump where it is being condensed. After several stages (Fig. 16 shows a three stage pump), an ultimate pressure of 10^{-5} Pa or better can be reached.

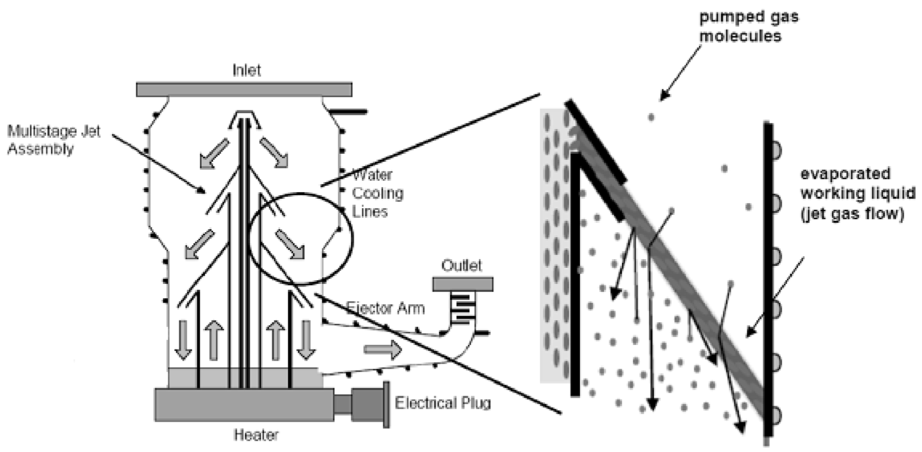


Fig. 16: Working principle of a vapour diffusion pump (cylindrical design).

The working principle is based on a momentum exchange between the gas that is being pumped and the jet gas (the evaporated working fluid) which is cycling inside the pump. Vapour diffusion pumps have no movable parts and the only electrical component is a heater plate that can be changed without venting the vacuum system. This makes the diffusion pump very reliable and practically maintenance-free. Vapour diffusion pumps are available with very high pumping speeds (up to > 50 m³/s). To reduce the backflow of the working fluid into the process chamber, a cooled baffle is needed what increases the complexity of the system. Diffusion pumps are the primary choice for a high vacuum pump that has to work reliably under rough (i.e. dust & dirty-)applications where other pumps cannot be used anymore (e.g. metallurgy).

- Metal foil pumps

Metal foil pumping is based on a Russian development lead by A. I. Livshits [18]. The working principle is as follows: A metal foil (e.g. niobium or vanadium) is irradiated by atoms, produced by an atomizer which is a hot metal rod at a temperature of several hundred degrees above room temperature or by plasma methods. Then, gases like hydrogen, deuterium or tritium can penetrate through the metal foil whereas helium, noble gases or other heavy impurities cannot penetrate (Fig. 17). During this process of gas separating, a pressure rise of up to four orders of magnitude was observed for the hydrogen isotopes (Fig. 18) [19]. This is why this arrangement of a metal foil together with an atomizer can also be used as pump. This metal foil pump works only for hydrogen isotopes as a pump, it is not applicable for pumping helium and other heavy gases.

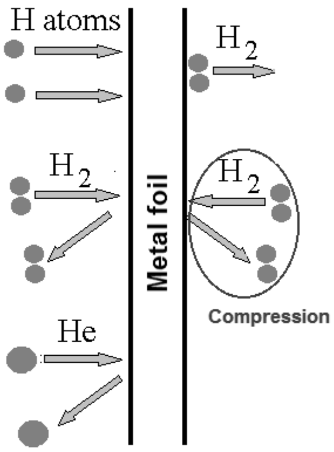


Fig. 17: Working principle of metal foil pumps

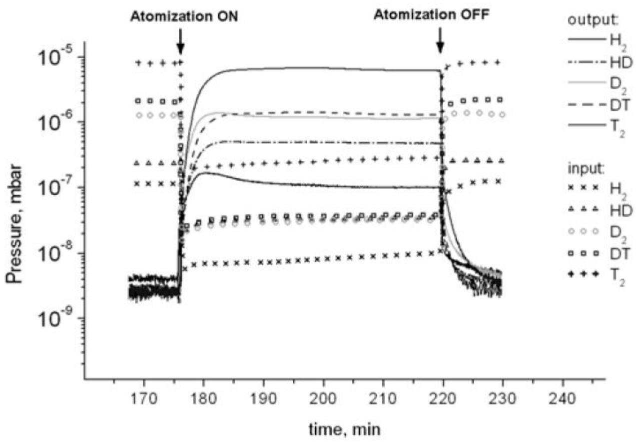


Fig. 18: Pumping effect of a superpermeable metal foil, investigated in PROMETHEUS [17]: A pressure rise after turning on the atomizer of almost four decades for hydrogen could be observed.

Gas binding vacuum pumps

- Cryo-condensation, cryo-frost or cryo-adsorption pumps

Cryo-condensation pumps are used where a high pumping speed (for all gases except He) and a clean vacuum is required, e.g. in current fusion machines like JET [20]. The physics principle is given by the fact that gases go into the condensed phase below their saturation temperature (by re-sublimation or condensation). Hence, the particles leave the gas volume and the gas pressure drops. The pumps consist of cold plates that are typically cooled by liquid or supercritical helium to temperatures between 1.8 and 4.5 K. The ultimate pressure of cryo-condensation pumps is limited by the sublimation pressure of the species which is illustrated for some gases in Fig. 19.

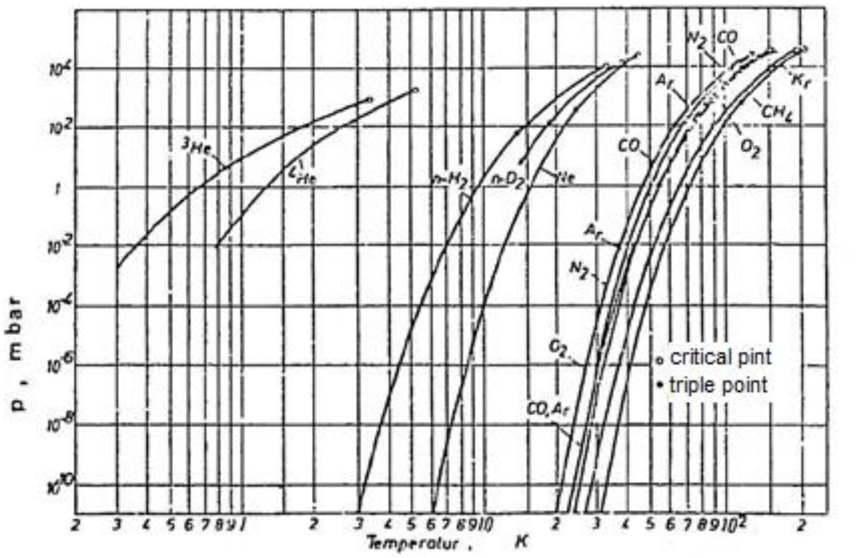


Fig. 19: Saturation pressure curves for various gases [21].

One of the main advantages of these pumps is their simple and robust construction. They are cheap (if a cryoplant for the cold supply is available anyway) and can be scaled up to the desired size (i.e. pumping speed and geometry) very easily. Unfortunately, they cannot pump helium as the condensation at 4.5 K or even 1.8 K is not possible. A solution to this is to provide a layer of condensed heavy gas (e.g. Argon), which has a frost structure so that the particles to be pumped can be incorporated (Ar-frost pump). Another option is the coating of the cryogenic surfaces by charcoal. This leads to huge sorption surfaces, the pumps are called cryo-adsorption pumps. Cryo-condensation or cryo- adsorption pumps are available not only custom-made with a connection to a cryogenic supply facility but also as commercial pumps for the lab where the low temperature is generated by a Gifford-McMahon cooler connected to a water cooled Helium compressor. Such pumps can reach UHV or even XHV at pumping speeds of some 10 m³/s, but only at relatively low pressures; otherwise the heat load to the cold surfaces gets too high. In the past, experiments have been conducted to build continuously working cryogenic pumps [22] or pumps that separate the gas internally by applying different temperature levels on the pumping surfaces [23].

- Titanium sublimation pump

The titan sublimation pump consists of a heated titanium wire that evaporates. This titanium vapour is condensed on the side walls of the pump at room temperature where it traps the gas molecules that are being pumped. Additional to that, the titanium will chemically combine with the gas molecules. Titan sublimation pumps can only work until the titanium wire is completely evaporated. The pumped gas cannot be processed and pump regeneration is not possible. The achievable pumping speed can be relatively large (given by the size and number of titanium wires inside), but the capacity is very small.

- Ion getter pump

The gas molecules that are being pumped in ion getter pumps are ionized in a high voltage discharge. In a magnetic field, provided by a permanent magnet, they are accelerated and directed into a titanium cathode to trap. The ejection of atoms out of a solid (titanium) surface due to the bombardment of fast (gas) particles is called sputtering. After the sputtering process, the titanium particles go to the anode wall again and trap the gas atoms that are being pumped. The pumping speed for noble gases is lower than for reactive gases but it is not zero. The lifetime of this pump depends on the pumped amount of gas. Gas cannot be processed and pump regeneration is also not possible. This pump will only work in a non-electric field environment as the external field would change the track of the ionized particles.

- NEG pumps

Non Evaporable Getter (NEG) pumps consist of metal alloy stripes or surfaces like Ti, Zr, V and Fe that provide actively pumping metal surfaces when activated (heated for a certain time to a temperature of several hundred °C) in vacuum. The gas molecules will be captured and pumped by chemisorption on the active metal surfaces when they impinge on it. This effect is strong for hydrogen and zero for noble gases. Once the material is fully loaded, regeneration can be done by heating up again to high temperatures. NEG pumps can be built custom-made in almost arbitrary size.

2.3 Vacuum pumping in fusion

2.3.1 Vacuum systems in fusion machines

Vacuum systems play a major role in fusion. Hundreds of these systems can be found all around the machine. In fusion reactors, i.e. on fusion machines using tritium or tritium mixtures as fuel, we can differentiate between two classes of vacuum system: Vacuum systems for processing non-tritiated gases and vacuum systems that have to process tritiated gases.

The vacuum systems for processing non-tritiated gases comprise a number of service vacuum systems that are responsible for evacuating e.g. the vacuum insulated cryogenic transfer lines, the plasma diagnostic and the plasma heating systems. Also the very large cryostat vacuum system, needed to maintain a good insulation vacuum (10^{-3} Pa region) for the cryogenically cooled superconducting magnets, has to handle only non-tritiated gases. The gas pumped by these systems is outgassing from walls and surfaces, entering through air leaks or escaping from the helium cooling system through leaks. These systems are all very different and use mainly commercially available pumps.

Vacuum systems that have to pump tritium can be found especially in the inner and the outer fuel cycle. Most important is the torus vacuum system, as part of the inner fuel cycle, that evacuates the plasma chamber (torus) where the hot plasma is magnetically confined. The vacuum on the inlet of the torus pumping ducts is in the order of 1 to 10 Pa during burn (the time when the plasma is on) and in the order of 10^{-4} Pa during dwell (the time when the plasma is off). The design of this system is crucial for the operation of the machine: During burn, the pressure has to be kept constant against a certain fuelling rate. During dwell the base pressure has to be reached in a given time to be able to start the next plasma pulse and to keep the availability of the machine high. This thesis focuses especially on the development of a vacuum pumping system for the inner fuel cycle.

In the outer fuel cycle, tritium has to be extracted from liquid breeder materials. Therefore, a method called Permeation Against Vacuum (PAV) [24] or Vacuum Sieve Tray (VST) [25] is under development. Both methods require large vacuum pumps, located close to the torus, that evacuate the PAV or VST systems in which the tritium is extracted out of the liquid breeder material. Though the development of vacuum pumps for the outer fuel cycle is not explicitly part of this work, it is expected that the pumps developed for the inner fuel cycle are also applicable here.

2.3.2 Special requirements to vacuum pumps in the inner fuel cycle

The use of vacuum pumps in the inner fuel cycle of fusion devices necessitates in some special requirements that are very unusual for most vacuum pumps outside fusion. The primary pumps used for torus pumping are typically installed very close to the torus in order to provide a high transmission probability and to keep conductance losses low. The requirements to these pumps are:

- A good resistance against neutronic radiation (the fusion reaction produces a huge neutron flux)
- A tolerance of ambient magnetic fields (the magnets are directly beside the pumps)
- Very low maintenance requirements (all work has to be done remotely due to radiation conditions)
- A good availability and a high reliability (the pumps are essential for machine operation),
- Very large pumping speeds (some 100 m^3/s), especially for light gases
- A large operational window (pressure 1 to 10 Pa during burn, < 10^{-4} Pa during dwell)
- Operation under dust & dirty environmental conditions (up to 2 kg dust per day might be produced due to wall erosion[1])
- Low tritium accumulation (licencing issues; tritium is very rare and expensive)
- Full tritium compatibility

The roughing pumps are not very close to the machine and installed in the tritium plant in some ten meter distance, so no radiation, dust, magnetic fields or remote maintenance requirements have to be met. However, huge pumping speed, high reliability and full tritium compatibility is still essential.

Tritium compatibility is an important issue: Tritium is the most disfavourable fluid to pump as it is radioactive and chemically extremely active. With water or polymers in seals, lubricants, electrical insulation etc., it makes a hydrogen exchange reaction and replaces the protium by tritium. It then decays with a half-life of 12.3 years towards He-3 what leads to a swelling effect followed by a decomposition of these substances. Especially fat or oil is destroyed after short exposure times. Tritium shows also a high diffusivity, meaning that small gaps e.g. in rotary feed-throughs (e.g. labyrinth seals) can be penetrated easily. Hermetically tight pumps without any polymers are thus crucial for vacuum pumps in tritium handling systems.

2.3.3 State-of-the-art in vacuum pumping in the inner fuel cycle

JET and TFTR are the only two machines that have ever been used a deuterium tritium fuel. This chapter discusses the torus vacuum system of both machines together with the ITER torus vacuum system that is mainly based on the scaling of the JET system. The ITER system is still under development and the exact configuration has not been frozen so far.

When TFTR was built in the early 1980s, non-tritium compatible pumping systems have been used and it was taken into account that the lifetime of the pumps is very limited and the oil has to be changed often due to cracking effects when getting in contact with tritium [26]. Also the production of activated (tritiated) oil was accepted at TFTR. All this might have been an option for a very first experimental device with short plasma pulses and a relatively low tritium inventory. But for larger

[1] Dust might stay inside the machine or penetrate through the pumping ducts towards the torus vacuum pumps where it is trapped or transported away. The formation and migration of dust is not yet fully understood and subject of ongoing research.

and more advanced machines this will not be an option for both, environmental and economic reasons.

JET has decided to go for a more tritium compatible pumping system, based on cryogenic primary pumps (and turbomolecular pumps) and mechanical and cryogenic roughing pumps. The cryogenic primary pumps are basically cold pipes, supplied with liquid helium, located inside the torus below the divertor that is the lowest part of the machine where the magnetic flux lines hit the walls and where the exhaust gas accumulates [20]. In total there are two independent pumps (∼ 100 m³/s pumping speed each), with a total length and height of 10 and 0.3 m, respectively. An Argon spray facility has been installed to allow helium pumping using Argon frost. In parallel to the cryopumps, four turbomolecular pumps by Varian (∼ 2 m³/s pumping speed each) have been installed on the torus. These pumps have been modified by the manufacturer towards all metal seals. However, they are not fully tritium compatible as internal polymers are still in contact with tritium. The cryogenic roughing pumps, located in the Active Gas Handling System (AGHS) some meters beside the torus building, work like condensers: Cold plates in a vessel are cooled using liquid helium and connected to the roughing lines. Here, three pumps installed in parallel; one of them is coated with charcoal. Also the cryogenic fore-vacuum pumps have to be regenerated from time to time, but into a smaller volume than the primary pumps, leading to a regeneration pressure high enough for all-metal scroll pumps. An overview on the primary- and roughing pumps for the three machines mentioned above is given in Tab. 5.

Tab. 5: Comparison of the primary- and roughing pump solutions for the torus vacuum system of TFTR, JET and ITER.

	TFTR [25]	**JET* [18, 98, 99]**	**ITER [97]**
Primary pumps	Turbo pumps	Pumped divertor (cryo-condensation pump) + Modified turbo pumps	Cryo-sorption pumps (Fig. 20)
Roughing pumps	Scroll pumps backed up by piston pumps	Cryogenic fore-vacuum (Cryo-sorption pumps) + mechanical forevacuum (all-metal scroll pumps, metal bellow pumps)	Cryo-Viscous Compressors (CVCs, Fig. 21) backed up by piston pumps

*configuration during tritium operation in the 1990’s

The primary pumps used in the ITER pumping systems are cryo-adsorption pumps developed by KIT [27, 28]. This pump type has been selected as it can be made easily tritium compatible and scaled to the desired size. Furthermore, the pumps do not have movable parts (except of the inlet valve), what has advantages in view of the surrounding magnetic fields and the expected dust (from torus wall erosion). As Ar-frost pumping for ITER would lead to unacceptable high gas loads to the tritium plant during regeneration (where also the frozen argon is released), it has been replaced by adsorption pumps that use charcoal coated surfaces to trap the gas.

Fig. 20 shows a CAD model of the ITER cryopumps: The charcoal coated 4.5 K panels can be seen in blue. They are surrounded by the thermal radiation and gas pre-cooling shields (green) at 80 K. These shields are necessary to keep the heat load due to the hot inflowing gas and the large radiation heat transfer from the pump housing to the panels low. Heat transfer by radiation has a strong effect on the thermal heat load to the cryogenic temperature level and must be minimized as much as possible: For thermodynamic reasons, cooling at 4.5 K is about 500 times less energy efficient than at 80 K. Each pump needs a huge valve box for cryogenic supply connected to a cryoplant with helium compressors in the MW-range. The six ITER cryo-adsorption pumps are connected via six direct pumping ports to the machine [29]. Each pump has a pumping speed of approx. 80 m³/s (for hydrogen) [28]. The pumps need to be regenerated when their capacity limit or the regulatory limit for maximum allowed tritium/hydrogen inventory is reached. One regeneration cycle (inlet valve closing → warming up to 100 K → gas release → cooling down to 4.5 K → valve opening) at ITER takes approx. 600 s [28]. For continuous machine operation, the operation and regeneration cycles for each pump can be done in a way that quasi-continuous pumping is possible. The pumps can provide a gas separation during regeneration, depending on the temperature of the sorption surface.

For the ITER rough pumping system, the combination of a cryo-viscous compressor (CVC) with a large and tritium compatible metal bellow pump (and potentially an additional scroll pump, if the ultimate pressure of the piston pump is not low enough) is foreseen [30]. The CVC is based on the JET cryogenic fore-vacuum system: The gas, coming from the fore-vacuum line in which the torus cryopumps are regenerated, is pre-cooled by an 80 K chevron baffle and finally condensed with 4.5 K supercritical helium (Fig. 21). The regeneration of the CVCs can be done to a higher pressure as the inventory-to-volume-ratio is large. At this pressure, the piston pumps can take over (typically at some hundred Pa).

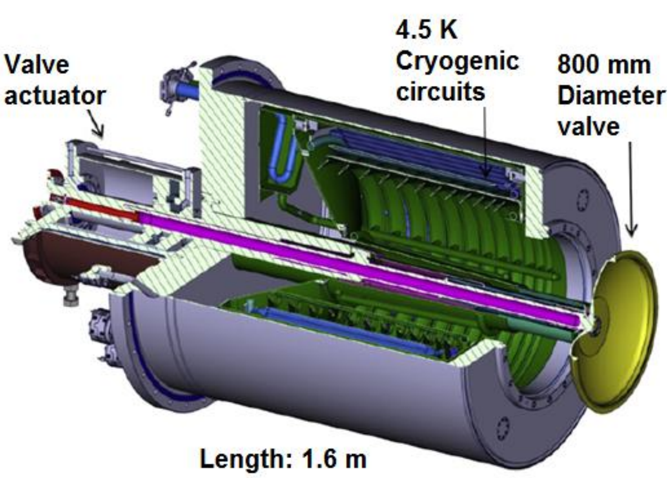


Fig. 20: CAD model of the ITER torus cryo-adsorption pump [28].

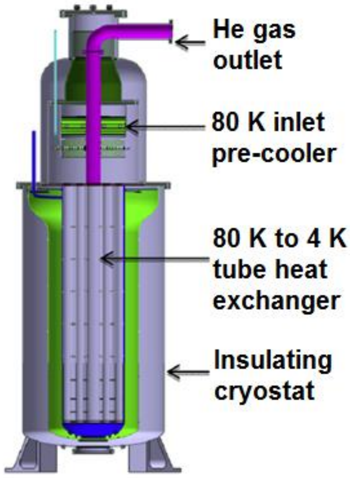


Fig. 21: CAD model of the ITER cryo-viscous compressor [30].

3. Scope of this work

In the framework of this PhD thesis, a vacuum pumping concept for torus pumping in future fusion power plants has to be developed.

In a former activity by EFDA, it has become obvious that scaling of the ITER-like vacuum pumping solution towards DEMO/fusion power plants is not an option [30]. The scaling issue comes especially from the fact that (i) huge inventories would accumulate in the ITER-like pumping system because of the discontinuous operation scheme, leading also to safety and licencing concerns and (ii) a low-temperature cryogenic pumping concept, based on a 4.5 K helium cryoplant will have some issues for future fusion reactors, mainly due to high investment- and operational costs and potential availability problems with the required quantities of helium as refrigerant. It was thus decided to address the lack of a suitable torus pumping solution in this thesis.

The development of the novel vacuum pumping concept started from scratch: In a first step, all requirements to the vacuum pumping system had to be collected. Based on that, an unbiased system engineering approach has been done that assessed all available vacuum pumping methods and identified the most promising ones.

Then it had to be ensured that the identified pumping methods are applicable for the vacuum conditions expected in fusion power plants. Therefore, experimental facilities had to be set up and proof-of-principle testing had to be done. Once this was successful, suitable vacuum pumps could be identified and a conceptual design for an advanced vacuum pumping system could be developed.

4. Development of novel vacuum pumping concept

4.1 Description of the general approach

The development of a novel vacuum pumping concept will be done as follows: In a first step, the core functions that have to be fulfilled by the torus pumping system have to be defined. Then, in the following step, a systems engineering approach will be made to assess available pumping methods. This approach shows how good different pumping methods fulfil the required functions on torus vacuum pumping in the inner fuel cycle. Based on this, a well-founded decision can be made leading to the selection of the most promising pumping solutions for a fusion power plant. Finally, the combination of the identified different pumping methods leads to a novel vacuum pumping concept for fusion power plants.

4.2 Core functions to be fulfilled by vacuum pumping

The core functions to vacuum pumping can be summarized by the following tasks that have to be fulfilled:

1. A vacuum level has to be provided that allows the start of a plasma pulse (< 5×10^{-4} Pa). This vacuum has to be reached in a given time (dwell time).
2. During plasma burn, the vacuum (1-10 Pa) in the torus has to be kept against a given fuelling rate.

Due to the large pressure range that has to be covered by this system, it is obvious that at least two pumping systems are required, primary pumping and rough pumping (see chapter 2.2). As these two methods may be completely different in their requirements and functions, the following identification process will be done separately for each pumping method.

4.3 Assessment of available pumping methods

4.3.1 Overview of the identification process

The identification process starts with a pairwise comparison (chapter 4.3.3) of different requirements to vacuum pumping and continues with the calculation of a quality ranking (chapter 4.3.5) for different pumping methods. These two steps are done separately for primary- and rough pumping.

The pairwise comparison approach is a method to obtain a ranking in an arbitrary list of different requirements [32]. The main idea behind this procedure is that it is easier to compare two aspects with each other than giving a full list a certain order. The pairwise comparison approach gives values expressing the relevance of each requirement [32]. These values are needed in the following step for the calculation of the quality rating. The quality rating expresses in a quantitative way (values between 0 and 100 %) how good a pumping method meets the requirements of the pairwise comparison.

4.3.2 Identification of requirements for pairwise comparison

Before a pairwise comparison can be done, the requirements have to be identified. This is a very important step because reliable results can only be obtained if all relevant requirements to the pumping system are considered. A summary of the requirements used for the pairwise comparison approach is given in Tab. 6.

Tab. 6: Requirements used for pairwise comparison.

Requirements used for the pairwise comparison approach	Primary pumping	Rough pumping
Reliable pumping process	X	X
No complex pumps required	X	X
No complex pump infrastructure required	X	X
Applicable for high throughputs	X	X
Good pumping for light gases	X	X
High pressure range can be covered	X	X
Scaling towards high pumping speeds possible	X	X
Low tritium accumulation during pumping	X	X
Gas separation during pumping	X	
Dust can be tolerated	X	X
Radiation can be tolerated	X	
Magnetic fields can be tolerated	X	
Seismic events can be tolerated	X	X
Pumping unaffected by machine failures	X	
Machine unaffected by pump failures	X	

The requirements considered for the primary pumping system are 15 in total. The process should allow reliable pumping without too complex pumps requiring a complex pumping infrastructure. A low complexity is always desirable as all access in case of maintenance or failures has to be done remotely due to a strong activation of all components by neutronic radiation.

Processing high gas throughputs, a good pumping capability for light gases and the covering of a large pressure range is also essential for the primary pumping system: In fusion devices, large gas throughputs are expected, mainly comprising the light gases deuterium and tritium that might be difficult to pump due to their high diffusivity through small gaps inside the pumps and their high molecular velocity (especially relevant for kinetic pumps). If the pressure range covered by a pumping method is too low, this would immediately lead to a complex, multi-stage pumping solution. A good scaling towards large pumping systems must be possible: If this cannot be realized, a larger number of pumps would be required leading again to a higher complexity of the whole system.

Tritium accumulation in the pumping system must be as low as possible and a gas separation during pumping should be possible as this would be a huge benefit for the overall pumping system. Tritium is very rare, expensive and radioactive. Therefore, it is obvious that the inventory should be minimized as much as possible. If the primary pumps could separate pure deuterium and tritium from the pumped gas, it could be recycled immediately as fresh fuel back to the machine, keeping the tritium systems for processing the exhaust gases small, i.e. with a low inventory. For a closer discussion of this concept, see chapter 4.6

The primary pumps are located very close to the machine to keep conductance losses of the pumping ducts low. Harsh environmental conditions like dust, (neutronic) radiation and ambient magnetic fields must thus be tolerated. Plasma operation inside the torus will lead to an erosion of the first wall material what forms dust that might penetrate to the pumps where it could cause problems. Neutronic radiation might affect electronics and sensors and could lead to the degradation of material properties inside the pumps. Also magnetic fields generated by the magnet system close by could affect electronics and would cause eddy currents in moving components (like in the rotors of kinetic pumps), leading to overheating problems. Furthermore, safety is extremely important for regulatory (nuclear licencing) and economic (high availability of the machine) reasons: Seismic events have to be tolerated and the pumping system should be unaffected by machine failures as well as the machine should be unaffected by pump failures: In case of earthquakes, the pumps must not be destroyed. In case of pump failures, this should not damage the machine by e.g. working fluids or pump components that reach the torus. Also if the machine fails by loss of vacuum- or loss of coolant accidents, the pumps should not be destroyed. For the rough pumping system, only 10 aspects will be considered. The ones related to the close location to the torus, like harsh ambient conditions, as well as the requirement for gas pre-separation can be abandoned. Aspects like reliable pumping, no complex pumps- and pumping infrastructure, applicability for high gas throughputs, a good pumping for light gases, the covering of a large pressure range and good scalability towards high pumping speeds are still important. Also safety issues like low tritium accumulation, tolerance of dust and seismic events are essential.

4.3.3 Pairwise comparison

The pairwise comparison is done according to the following scheme: If one category is more important than the other, a 2 is given; if it is less important, a 0 is given; if both categories are of the same importance, a 1 is given. The results for primary- and rough pumping methods are shown in Tab. 7 and Tab. 8, respectively.

Tab. 7: Pairwise comparison results for primary pumping.

	Reliable pumping process	Applicable for high throughputs	High pressure range can be covered	Scaling towards high pumping speeds	No complex pumps required d	No complex pump infrastructure required	Low tritium accumulation during pumping	Pumping unaffected by machine failures	Machine unaffected by pump failures	Dust can be tolerated	Radiation can be tolerated	Magnetic fields can be tolerated	Seismic events can be tolerated	Good pumping for light gases	Gas separation during pumping	**SUM**	**ORDER**
Reliable pumping process		1	2	1	1	2	1	1	0	1	1	1	1	1	1	**15**	**6**
Applicable for high throughputs	1		2	2	2	2	1	0	0	1	1	1	1	1	1	**16**	**5**
High pressure range can be covered	0	0		1	2	2	0	0	0	1	0	0	0	1	0	**7**	**9**
Scaling towards high pumping speeds	1	0	1		2	2	1	1	0	1	0	0	0	1	0	**10**	**8**
No complex pumps required	1	0	0	0		1	0	1	0	0	0	0	0	0	0	**3**	**10**
No complex pump infrastructure required	0	0	0	0	1		0	0	0	0	0	0	0	0	0	**1**	**11**
Low tritium accumulation during pumping	1	1	2	1	2	2		2	1	1	1	1	1	1	1	**18**	**4**
Pumping unaffected by machine failures	1	2	2	1	1	2	0		0	1	1	1	1	1	1	**15**	**6**
Machine unaffected by pump failures	2	2	2	2	2	2	1	2		1	1	1	1	2	2	**23**	**1**
Dust can be tolerated	1	1	1	1	2	2	1	1	1		1	1	1	2	0	**16**	**5**
Radiation can be tolerated	1	1	2	2	2	2	1	1	1	1		1	1	2	1	**19**	**3**
Magnetic fields can be tolerated	1	1	2	2	2	2	1	1	1	1	1		0	0	1	**16**	**5**
Seismic events can be tolerated	1	1	2	2	2	2	1	1	1	1	1	2		2	2	**21**	**2**
Good pumping for light gases	1	1	1	1	2	2	1	1	0	0	0	2	0		0	**12**	**7**
Gas separation during pumping	1	1	2	2	2	2	1	1	0	2	1	1	0	2		**18**	**4**

The red numbers in the first category (*Reliable pumping Process*) shall illustrate this procedure by an example (red in Tab. 7): A reliable pumping process is more (2) important than the lack of a complex infrastructure whereas the reliable pumping process is not so important (0) than the fact that the machine stays unaffected by potential pump failures. The reliability of the pumping process is of same importance (1) than the toleration of seismic events.

The order of importance for each aspect on the pumping method, found by this method, is shown in the very right columns of these figures. The quantitative weighting, required for the following calculation of the quality ranking, is given in the neighbouring column (SUM-value). For filling the matrix diagram, it is sufficient to fill only the numbers on the right side of the diagonal line (indicated in black). The numbers in grey are resulting and can be calculated by two minus the value reflected on the diagonal line.

Not very surprising, safety aspects (machine unaffected by pump failures; seismic events) are most important for primary pumping, followed directly be the requirement of a low tritium accumulation in the process and the possibility of gas separation. Pumping of dust and the operational requirements like the toleration of the harsh environmental conditions are the next important aspects, followed by a good pumping capability for light gases and a good scalability towards large pumping speeds. The least important is the requirement of a low complexity of the system (i.e. a cheap system), thought this would be very advantageous in view of the application of this pumping system in machines that should be economically successful.

Tab. 8: Pairwise comparison results for rough pumping.

	Reliable pumping process	Applicable for high throughputs	High pressure range can be covered	Scaling towards high pumping speeds	No complex pumps required	No complex pump infrastructure required	Low tritium accumulation during pumping	Dust can be tolerated	Seismic events can be tolerated	Good pumping for light gases	**SUM**	**ORDER**
Reliable pumping process		1	2	1	1	2	1	1	1	1	**11**	**4**
Applicable for high throughputs	1		2	2	2	2	1	1	1	1	**13**	**2**
High pressure range can be covered	0	0		1	2	2	0	1	0	1	**7**	**6**
Scaling towards high pumping speeds	1	0	1		2	2	1	1	0	1	**9**	**5**
No complex pumps required	1	0	0	0		1	0	0	0	0	**2**	**7**
No complex pump infrastructure required	0	0	0	0	1		0	0	0	0	**1**	**8**
Low tritium accumulation during pumping	1	1	2	1	2	2		1	1	1	**12**	**3**
Dust can be tolerated	1	1	1	1	2	2	1		1	2	**12**	**3**
Seismic events can be tolerated	1	1	2	2	2	2	1	1		2	**14**	**1**
Good pumping for light gases	1	1	1	1	2	2	1	0	0		**9**	**5**

4.3.4 Identification of pumping methods for quality rating calculation

The relevant pumping methods to be used for the calculation of a quality rating have been identified based on the well-known pump tree (Fig. 9 in chapter 2.2). Nine methods have been identified for primary pumping and six for rough pumping.

For primary pumping, all methods based on gas binding are considered (Tab. 9): getter pumping with and without regeneration, cryo-condensation and –adsorption pumping, cascaded and continuous cryo-pumping. In view of the gas transfer pumps, all pumping methods able to reach at least high vacuum conditions have been considered (except of ion transfer pumps as they are XHV pumps not able to process gas in remarkable quantities): kinetic pumping, vapour diffusion- or ejector pumping and metal foil pumping (superpermeable pumping).

For rough pumping, the following methods are considered: adsorption pumping, cryo-condensation and cryo-adsorption pumping, kinetic pumping, reciprocating- and rotating positive displacement pumping (Tab. 9).

Tab. 9: Pumping methods identified for the calculation of a quality ranking.

Pumping methods identified for primary and rough pumping	Primary pumping	Rough pumping
Getter pumping (regeneration possible)	X	
Getter pumping (regeneration not possible)	X	
Adsorption pumping		X
Cryo-condensation pumping	X	X
Cryo-adsorption pumping	X	X
Cascaded cryopumping	X	
Continuous cryopumping	X	
Kinetic pumping	X	X
Vapour diffusion/ejector pumping	X	
Metal foil pumping (superpermeable pumping)	X	
Reciprocating positive displacement pumping		X
Rotating positive displacement pumping		X

4.3.5 Calculation of a quality rating

The quality rating is conducted in such a way that it is checked to what extent a pumping method meets the categories already used for pairwise comparison. For this purpose, the resulting weighting value g (SUM value) for each category is taken and multiplied with a rating number q according the German guideline for this approach [32]. The value of the rating number has to be chosen from q = 0 (dissatisfying), 1 (inadequate), 2 (sufficient), 3 (good) or 4 (very good, ideal). Finally, the quality rating W is given in a relative way, related to the maximum number of points that is 4 (best rating) x 210 (sum of all weighting values) = 840, and expressed as a number in per cent. The results are shown in Tab. 10 and Tab. 11, separately for the primary and the rough pumping methods.

Tab. 10: Quality rating calculation results for primary pumping.

	Weighting	Getter pumping (regeneration possible)		Getter pumping (regeneration not possible)		Cryo-condensation pumping		Cryo-adsorption pumping		Continuous cryo-pumping		Cascaded cryo-pumping		Kinetic pumping		Vapour diffusion/ejector pumping		Metal foil pumping (superpermeable pumping)	
		p	**p x g**	**p**	**p x g**	**p**	**p x g**	**p**	**p x g**	**p**	**p x g**	**p**	**p x g**	**p**	**p x g**	**p**	**p x g**	**p**	**p x g**
Reliable pumping process	**15**	1	15	1	15	3	45	3	45	1	15	1	15	0	0	3	45	1	15
Applicable for high throughputs	**16**	1	16	0	0	3	48	4	64	3	48	3	48	3	48	4	64	3	48
High pressure range can be covered	**7**	2	14	2	14	3	21	4	28	3	21	3	21	2	14	3	21	1	7
Scaling towards high pumping speeds	**10**	3	30	3	30	4	40	4	40	3	30	3	30	0	0	4	40	3	30
No complex pumps required	**3**	3	9	1	3	4	12	3	9	0	0	0	0	0	0	4	12	1	3
No complex pump infrastructure required	**1**	3	3	1	1	0	0	0	0	0	0	0	0	4	4	1	1	2	2
Low tritium accumulation during pumping	**18**	0	0	0	0	0	0	0	0	1	18	0	0	4	72	3	54	4	72
Pumping unaffected by machine failures	**15**	1	15	1	15	3	45	3	45	3	45	3	45	1	15	3	45	1	15
Machine unaffected by pump failures	**23**	4	92	4	92	2	46	2	46	2	46	2	46	3	69	2	46	3	69
Dust can be tolerated	**16**	1	16	1	16	4	64	1	16	1	16	1	16	0	0	3	48	2	32
Radiation can be tolerated	**19**	2	38	2	38	4	76	4	76	4	76	4	76	1	19	3	57	3	57
Magnetic fields can be tolerated	**16**	3	48	2	32	3	48	3	48	2	32	3	48	1	16	3	48	3	48
Seismic events can be tolerated	**21**	3	63	3	63	3	63	3	63	2	42	3	63	1	21	3	63	3	63
Good pumping for light gases	**12**	3	36	3	36	0	0	3	36	0	0	1	12	1	12	4	48	4	48
Gas separation during pumping	**18**	0	0	0	0	0	0	0	0	0	0	4	72	0	0	0	0	4	72
Sum:	**210**	**395**		**355**		**508**		**516**		**389**		**492**		**290**		**592**		**581**	
Quality rating W:		**47.0**		**42.3**		**60.5**		**61.4**		**46.3**		**58.6**		**34.5**		**70.5**		**69.2**	

For primary pumping, vapour diffusion (or diffusion-ejector) pumping shows the highest quality rating with a value above 70 %. Second and third best suitable method is metal foil- and cryo-adsorption pumping with rating values of 69 % and 61 %, respectively.

For rough pumping, the highest values are achieved by rotating- and reciprocating positive displacement pumping with values of 93 % and 67 %, respectively. On third position is again cry-adsorption pumping (53 %).

Tab. 11: Quality rating calculation results for rough pumping.

	Weighting	Adsorption pumping		Cryo-condensation pumping		Cryo-adsorption pumping		Reciprocating positive displacement pumping		Rotating positive displacement pumping		Kinetic pumping	
		p	**p x g**	**p**	**p x g**	**p**	**p x g**	**p**	**p x g**	**p**	**p x g**	**p**	**p x g**
Reliable pumping process	11	2	22	3	33	3	33	2	22	4	44	1	11
Applicable for high throughputs	13	1	13	3	39	3	39	2	26	4	52	4	52
High pressure range can be covered	7	1	7	0	0	0	0	2	14	3	21	3	21
Scaling towards high pumping speeds	9	1	9	3	27	3	27	2	18	4	36	4	36
No complex pumps required	2	0	0	3	6	3	6	2	4	3	6	0	0
No complex pump infrastructure required	1	1	1	0	0	0	0	4	4	3	3	3	3
Low tritium accumulation during pumping	12	0	0	0	0	0	0	4	48	4	48	4	48
Dust can be tolerated	12	1	12	3	36	2	24	1	12	4	48	1	12
Seismic events can be tolerated	14	4	56	3	42	3	42	4	56	3	42	0	0
Good pumping for light gases	9	3	27	0	0	2	18	4	36	4	36	1	9
Sum:	**90**	**147**		**183**		**189**		**240**		**336**		**192**	
Quality rating W:		**40.8**		**50.8**		**52.5**		**66.7**		**93.3**		**53.3**	

4.3.6 Discussion of the identification process results

Primary pumping

Vapour diffusion pumping is the solution of primary choice in this identification process, mainly due to the fact that this method works continuously and does not accumulate tritium like cryogenic- or getter pumping. It is also very resistant to dust that may penetrate the pumping ducts and finally reaches the pumps and harsh environmental conditions (e.g. magnetic fields) as no movable components are required for realizing this pumping method. This is also the reason why diffusion pumping is considered as very reliable. To realize vapour diffusion pumping, a tritium resistant working fluid is needed. As all organic materials (like the normally used diffusion pump oils) are excluded (see explanation in chapter 2.3.2), the only available material that can be evaporated at reasonable temperatures is mercury, already been used in the past for almost 50 years in diffusion pumping. As mercury is known to be perfectly tritium compatible [33], it is suggested to take the step back to mercury diffusion pumps. In addition, an "excellent reliability" was reported for former fusion devices using mercury diffusion pumps [34]. Mercury thus seems to be the only option if diffusion pumping shall be realized in DEMO. A more detailed discussion of the working fluid is given in chapter 4.5.

Metal foil pumping, the second-promising solution for primary pumping, is again a continuously working pumping method without movable parts that provides pumping for hydrogen only; all other gases cannot be pumped by this method. In consequence, metal foil pumping alone cannot be used for primary pumping; but a combination with another continuously working pumping method, like diffusion pumping, will solve this problem. Moreover, it would be a perfect supplementation for diffusion pumping as it would allow for continuous pumping including gas separation. This combination is thus being identified as most promising primary pumping method.

The third best solution for primary pumping, cryo-adsorption pumping, is the reference solution for ITER [28]. The advantage here is clearly that the process can be realized by relative simple pumps. In addition, the required cryogenic infrastructure is anyway available, so no additional effort is needed here. (For DEMO, this may be different if the magnet system uses high-temperature superconductors operated at elevated temperatures.) A big disadvantage for this pumping solution is its pulsed operation leading to the accumulation of tritium and complex regeneration cycles with strongly pulsed heat loads to the cryoplant [29]. For ITER, an experimental device with only short- to medium pulsed plasma operation and very few pulses per day, tritium inventory is not a mayor issue. Continuous operation is for the same reasons also not required and long-term reliability and economic considerations plays only a secondary role. In conclusion, cryo-adsorption pumping will be a good solution for ITER, but for DEMO or even fusion power plants, all disadvantages mentioned before have the potential to become a serious show-stopper or at least a good reason for preferring another pumping solution for a new vacuum pumping concept.

All other pumping methods discussed in the assessment for primary pumping show a very bad performance. The most important disadvantages for getter pumping is (i) the accumulation of tritium in the material and (ii) the irreversible damage of the getter material when getting in contact with water vapour or oxygen requiring an exchange of the getter (depending on the getter material). The latter would lead to an irreversible strong decrease of the pump capacity and pumping performance in case of a safety event, like a water leak into the torus or leaks that allow the entering of oxygen. For kinetic pumping, there is the issue of fast rotating rotor blades in magnetic fields (generation of eddy currents lead to overheating) and under harsh conditions (tritium, dust) and limited available sizes. Theoretically, a shielding can be done for this kind of pump, but this is a complex task, leading to huge pumps and the installation of ferromagnetic materials close to the complex and sensitive magnet system of the machine [35]. Furthermore, tritium will affect the organic insulation of the internal electric drive, leading to decomposition and a contamination of the processed gas [36]. Continuous or cascaded cryopumping is similar to cryopumping; some advantages (continuous operation or gas separating) are overcompensated by huge additional efforts (size and complexity) for such systems.

<u>Rough pumping</u>

The two most promising methods for rough pumping are rotating and reciprocating positive displacement pumping. Rotating pumps have the strong advantage over reciprocating pumps that no internal inlet and outlet valves are required and thus maintenance requirements are much lower. Therefore, reciprocating positive displacement pumping is the method preferred for the novel pumping concept. As both pumping methods require mechanical pumps, the technical realization of these processes is not easy. Details will be discussed in the next chapter.

The other rough pumping methods exhibit significant disadvantages compared to positive displacement pumping: The most important for cryo-based and adsorption based pumping is the huge tritium inventory and the complex required infrastructure. Such a pumping system would need, even when operated as roughing pump, another pumping system for regeneration and compression towards atmospheric pressure. For kinetic pumping, a compression of three decades cannot be achieved with currently available methods, especially not for light gases like hydrogen. Also this method would thus require another pumping system.

In conclusion, the pumping system identified in this theoretical approach is based on a combination of metal foil- and mercury vapour diffusion pumping for primary pumping and on rotating positive displacement pumping for rough pumping.

4.4 Assessment of rotating positive displacement pumping

Rotating positive displacement pumping can be realized using different pumps based on different working principles. A closer look to the pump tree (Fig. 9) gives the following options:

- Rotary vane pumping
- Roots pumping
- Screw pumping
- Scroll pumping
- Liquid ring pumping

In this chapter, these five methods are assessed as already done for the pumping methods described above. In addition, a technical-economic examination is being done to find out which of these methods is the most mature one.

From the five pumping methods considered here, rotary vane pumping requires a lubricant and liquid ring pumping a working fluid. As working fluid for ring pumping, mercury is assumed for tritium compatibility reasons (see chapter 4.3.6). This can be done as the working fluid does not have a lubricating function, as it is the case for rotary vane pumping. For the rotary vane pumping, only oil can be used as mercury is not able to provide this function.

Pairwise comparison

As all positive displacement pumping methods are rough pumping methods, the same aspects are used as already done for the pairwise comparison approach (Tab. 8). In addition three aspects are included, namely (i) the possibility of oil free pumping, (ii) manufacturer dependency and (iii) maintenance requirements. The identification of a working principle is close on a technical solution, so these detailed aspects can be included here.

Oil-free pumping describes the possibility to avoid (non-tritium compatible) oil in the pumps and means either dry pumping or the replacement of oil by other tritium-compatible fluids (like mercury). For some pumping solutions, very few – or only a single – manufacturer is on the market. A good example is Normetex®, a manufacturer of large and dry scroll pumps often used for tritium processing. Just recently, this company left the market and was re-founded as EUMECA®. Despite of this, the availability of such pumps on the market is still unclear. This shows how large the risk can be if one relies on only one manufacturer.

The results of the pairwise comparison are shown in Tab. 12. Not very surprising, it is similar to what was found in chapter 4.3.3. Concerning the three new aspects, oil-free pumping is the second important one.

Tab. 12: Pairwise comparison for the identification of rotating positive displacement pumping methods.

	Reliable pumping process	Applicable for high throughputs	High pressure range can be covered	Scaling towards high pumping speeds	No complex pumps required	No complex pump infrastructure required	Low tritium accumulation during pumping	Dust can be tolerated	Seismic events can be tolerated	Good pumping for light gases	Oil-free pumping possible	Low dependency on manufacturer	Low maintenance requirements	**SUM**	**ORDER**
Reliable pumping process		1	2	1	1	2	1	1	1	1	0	1	1	**13**	**4**
Applicable for high throughputs	1		2	2	2	2	1	1	1	1	0	1	1	**15**	**3**
High pressure range can be covered	0	0		1	2	2	0	1	0	1	0	2	1	**10**	**6**
Scaling towards high pumping speeds	1	0	1		2	2	1	1	0	1	1	2	1	**13**	**4**
No complex pumps required	1	0	0	0		1	0	0	0	0	0	1	0	**3**	**9**
No complex pump infrastructure required	0	0	0	0	1		0	0	0	0	0	2	0	**3**	**9**
Low tritium accumulation during pumping	1	1	2	1	2	2		1	1	1	1	2	2	**17**	**2**
Dust can be tolerated	1	1	1	1	2	2	1		1	2	1	2	2	**17**	**2**
Seismic events can be tolerated	1	1	2	2	2	2	1	1		2	1	2	2	**19**	**1**
Good pumping for light gases	1	1	1	1	2	2	1	0	0		1	0	2	**12**	**5**
Oil-free pumping possible	2	2	0	1	2	2	1	1	1	1		2	2	**17**	**2**
Low dependency on manufacturer	1	1	0	0	1	0	0	0	0	2	0		2	**7**	**8**
Low maintenance requirements	1	1	1	1	2	2	0	0	0	0	0	0		**8**	**7**

Calculation of a quality rating

The results for the quality rating are shown in Tab. 13. The solution with the highest quality is liquid ring pumping (89 %), followed by screw (70 %), roots (67 %) and rotary vane (65 %) pumping. This can be explained by the very simple and robust design required for ring pumping and the much more complex requirements to a pumping system based on screw, roots or rotary vane pumps. Scroll pumping shows the lowest rating as scroll pumping has a bad performance in pumping light gases, high maintenance requirements and a strong manufacturer dependency.

Tab. 13: Results for the calculation of a quality rating.

	Weighting	Rotary vane pumping		Roots pumping		Screw pumping		Scroll pumping		liquid ring pumping	
		p	p x g	p	p x g	p	p x g	p	p x g	p	p x g
Reliable pumping process	13	3	39	3	39	3	39	1	13	4	52
Applicable for high throughputs	15	3	45	2	30	3	45	1	15	4	60
High pressure range can be covered	10	4	40	2	20	4	40	2	20	2	20
Scaling towards high pumping speeds	13	2	26	3	39	3	39	2	26	4	52
No complex pumps required	3	3	9	1	3	1	3	1	3	4	12
No complex pump infrastructure required	3	4	12	4	12	4	12	4	12	1	3
Low tritium accumulation during pumping	17	3	51	4	68	4	68	4	68	3	51
Dust can be tolerated	17	1	17	1	17	0	0	0	0	4	68
Seismic events can be tolerated	19	4	76	2	38	2	38	2	38	4	76
Good pumping for light gases	12	3	36	2	24	2	24	1	12	3	36
Oil-free pumping possible	17	0	0	4	68	4	68	4	68	4	68
Low dependency on manufacturer	7	4	28	4	28	4	28	0	0	4	28
Low maintenance requirements	8	3	24	3	24	3	24	1	8	3	24
Sum:	**154**	**403**		**410**		**428**		**283**		**550**	
Quality rating w:		**65.4**		**66.6**		**69.5**		**45.9**		**89.3**	

Technical economic examination

The quality rating does not consider the costs for research and development efforts. A pumping solution can be high in quality but needs a lot of expensive and time consuming developing effort to be customized for the required application. This would relativize the high quality of the solution and is taken into account by the so-called technical economic examination.

For the technical economic examination, the expected costs for the pumps, including the estimated development effort, is plotted in per cent of the most expensive solution over the quality rating calculated before.

Screw pumps are considered as the most expensive solution (100%) as several pumps have to be connected in series to provide a good pumping of light gases and the development effort of a fully tritium compatible pump is very high: dry screw pumps are typically made out of black steel with internal polymer coatings for corrosion protection. Both is prohibited for fusion applications as black steel has a high permeability for hydrogen and polymers will be decomposed by tritium. The change of pump materials asks for different manufacturing methods and leads to a high investment in R&D. In addition, high-speed rotary feed-throughs (the screws run at 3000 to 6000 rpm) are required that are fully leak-tight (10^{-9} mbar l/s or better). This asks for magnetic coupling and – most probably – for a magnetic levitation of the large internal screws that need to be perfectly synchronized, even in case of a safety event, to avoid a contact of both screws what would result in a serious crash and destruction of the pump.

Scroll pumps show a very bad pumping for hydrogen asking for a combination of three or more very large scroll pumps [14]. This means a large number of these very expensive pumps would be required for the pumping of fusion reactors. Today, only one manufacturer is on the market (EUMECA, Augusta, GA, US) that provides tritium compatible, i.e. all-metal scroll pumps. In view of costs, this pumping solution is expected to be as expensive as screw pumping, or even more expensive, but with the advantage that no R&D is required anymore (90 %, numbers estimated based on the discussion presented here).

Roots pumps have the same disadvantages of screw pumps (serial pump arrangement, black steel, high-speed mechanical feed-throughs). However, as the pumps are smaller and easier to manufacture, the costs of such a pumping solution is expected to be smaller than for screw pumping (80 %).

Rotary vane pumps are needed in a dry version. This development would not start at zero – there are already some small-size pumps available on the market – but these pumps still need significant improvement to reach the required low inlet pressures and pumping speeds. Rotary vane pumps are typically made out of black steel and with standard (i.e. oil or fat lubricated) bearings and mechanical feed-throughs. Also here, a lot of development effort would be needed to make this version tritium compatible. On the other hand, if successful, it is likely that one pump alone could fulfil the pressure and pumping speed requirements. This pumping solution is thus expected to be less expensive than roots pumping (60 %).

Liquid ring pumps are already available as stainless-steel version and with dry (i.e. ceramic) bearings and with magnetic coupling between internal rotor and the electric drive. Due to their simple design, the cost for such a pump is low and potential changes on the pump design can be done relatively easy. Liquid ring pumps are thus expected as cheapest solution (20 %).

Fig. 22 illustrates the outcome of the technical economic examination. In this figure, the best solutions can be found in the lower right corners, where the quality rating is high and the costs for the pumps including R&D efforts are low at the same time. In our case, only one solution is in this region of interest: liquid ring pumping. Liquid ring pumping is the most promising pumping method for positive displacement pumping as it provides a high quality solution at low development costs.

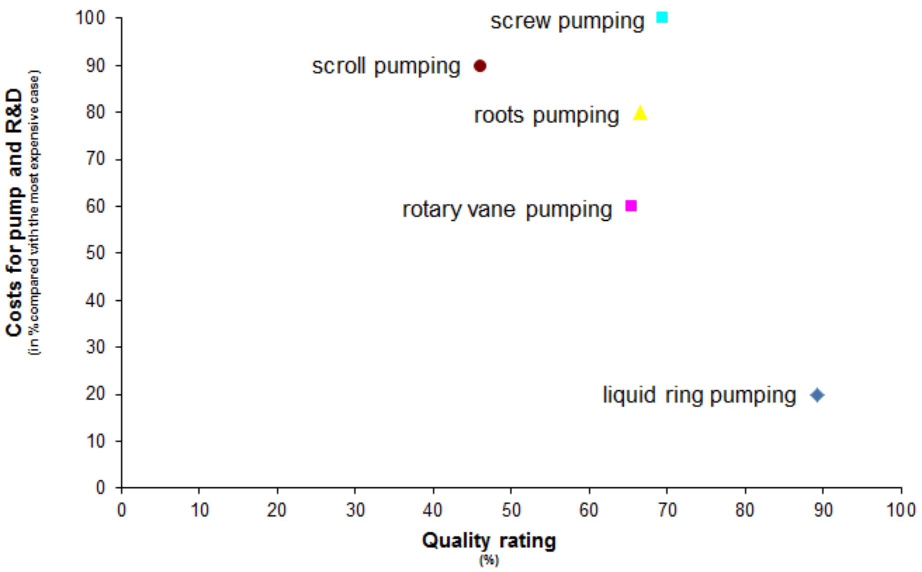


Fig. 22: Results of the technical-economic examination.

4.5 Discussion of mercury as working fluid

Mercury is very bio-toxic, could propagate in the whole vacuum system and is more and more banned from the global market for health- and safety reasons (Minamata convention on mercury [37]) what may lead to an availability problem. Other issues with this working fluid may result by

- strong and long-term mercury activation due to neutronic irradiation,
- electrodynamic effects (no mercury flow possible inside the pumps) resulting by magnetic fields around the primary pumps and
- a strong solubility issues of tritium in mercury (high inventory).

In this chapter it shall be assessed if these considerations are critical or even a show-stopper for future fusion applications and if mercury alternatives are available.

Toxicity of mercury is not considered as critical, because a multilevel confinement approach has to be done anyway for the system containing the radioactive and much more toxic tritium. Mercury propagation in the pumping system can be avoided easily be cold traps (baffles) that have to be included in the pump design. This method seems to be fully sufficient for keeping the torus of the fusion devices free of mercury vapour. Mercury vapour contamination has not been an issue for fusion machines in the past [38].

Concerning the Minamata-Convention, mercury in fusion applications is not explicitly mentioned. This means the use for this purpose will not be prohibited. The only problem in long-term view may result by the prohibition of mercury mining and the disposal of mercury returning from a number of applications where the substitution by other substances is possible [37]. This could lead to long-term mercury shortness. However, this is more a political problem and not a problem associated with the running out of (natural) resources.

Neutronic irradiation

In the following chapter, a rough and worst-case estimation of the effect of neutronic irradiation to the mercury inside the pump is given. It would be a serious problem if mercury is being activated and generates long-term radioactive isotopes. Neutronic calculations require very complex Monte-Carlo simulations that require huge computational efforts and the exact knowledge of the boundary conditions (like geometries, neutron energy spectra, materials incl. impurities etc.). As these calculations cannot be done within the scope of this work; it was thus decided to use already existing calculations for the estimation of the activation of mercury that have been done for the DEMO models discussed within the European PPCS [3, 4].

For the calculation of activation data in general, work was started within the European Fusion Programme and led to the European Activation System (EASY) [39]. The 2007 version (EASY-2007) used for the neutronic irradiation calculations shown below is based on an extensive neutronic database, the European Activation File (EAF). It contains decay data, biological hazard coefficients, clearance data, cross section- and gamma adsorption data and an inventory code (FISPACT).

As a relevant and simple to understand value, the 'Clearance Index' can be calculated for mercury and plotted over the time. The Clearance Index of a material determines with which precautions it has to be handled according to IAEA guidelines. If less than 1, the material can be disposed as if it is non-radioactive, i.e. with no special precautions [39]. A clearance index of unity refers to an acceptable dose rate of 10^{-9} Sv/h [40]. The neutron spectrum used here is shown in Fig. 23. It is based on a typical deuterium/tritium plasma in a fusion power plant, described in Model A of the European power plant conceptual design study (PPCS) [41]. Furthermore, a neutronic irradiation of $2.5\cdot10^{12}$ $ncm^{-2}s^{-1}$ over a time period of 25 years was assumed for clearance index calculations. The red dash-dotted line in Fig. 24 describes the conditions at the thermal shield position of the machine, a location where identical conditions as for primary pumps can be assumed. A sharp decline that falls below 1 can be observed after approx. 100 years. This is in line with what is assumed as acceptable value for future fusion reactors and denotes that no negative surprises concerning mercury activation is expected.

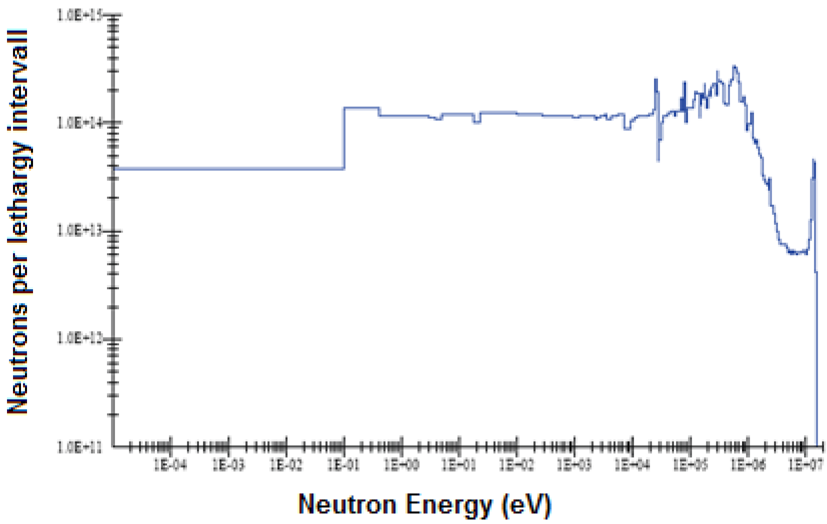


Fig. 23: Energy spectrum of DEMO relevant neutrons expected at the radiation shield [39].

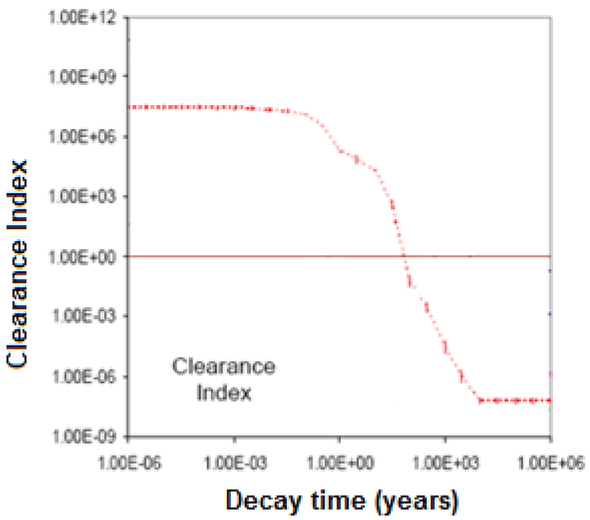


Fig. 24: Clearance index as function of time after shut-down of the machine [39].

Electrodynamic effects

If an electric conductor like mercury is moved in a magnetic field, a current is induced (basic principle of electrodynamics). This may disturb the operation of diffusion pumps in magnetic fields by decelerating or deflecting the mercury flows. The flows that may be affected by the magnetic field below the divertor are (i) the liquid mercury flow from the cooled walls into the boiler and (ii) the vapour flow from the boiler through the nozzle system towards the walls.

Liquid mercury has a relatively good electric conductance (10^6 A/(V·m) [42]). It can thus be assumed that it will be influenced by the field. But the influence on the moving mercury depends on the flow speed in the mercury back to- and through the boiler. Assuming an evaporation rate of 60 g/s (what is assumed the amount needed for the operation of a large diffusion pump) this equals a flow rate of approx. 4.5 ml/s through the boiler. The resulting flow speed – when assuming a boiler volume of several litres – is so low, that the influence of the magnetic field can be neglected, especially if the field strength is relatively weak (assuming an ITER design value of 10 – 100 mT; approx. 100 – 1000 Gauß [43]).

In the gaseous phase, mercury has a neglectable low electric conductance (10^{-12} Ω^{-1} cm^{-1} at 3.5 MPa [44]; at lower pressures even lower). The effect of ablation plays thus only a minor role, even if the flow speed of the mercury vapour is in the supersonic region. During simulations it has been found that the influence of the vapour jet speed on the pumping speed is weak. Even a deceleration of the jet speed by some percent would not have a strong influence on the pump performance.

Tritium solubility in mercury

An average tritium concentration of 8.5 μCi/kg was found in mercury which was used for 25 years in Sprengel pumps [45] (a pump type, where an extensive contact between mercury and tritium takes place). This equals $8.8 \cdot 10^{-11}$ mass% of tritium in mercury. Although this is far more than the solubility of protium in mercury ($5.0 \cdot 10^{-14}$ mass% [46]), the amount of tritium in mercury is so low that it can be neglected. In one ton of mercury, less than $1 \mu g$ of T_2 can be dissolved.

Based on the discussions above, the conclusion can be drawn that mercury can be used for diffusion pumping. Neutronic radiation, electrodynamic effects and tritium inventory is not considered as show-stopper. Moreover, mercury diffusion pumping has a number of additional benefits: It provides a very good pumping performance for light gases (like hydrogen and helium) and allows for a high foreline resistance because the momentum transfer between the mercury vapour and the pumped gas particles is ideal due to its high molecular mass.

Finally, it must also be noted that mercury will get very important for another fusion applications, where also no alternative is available, namely for the enrichment of the Li-6 required for tritium breeding.

4.6 *Direct Internal Recycling*

ITER will require a very large tritium processing facility (tritium plant) that removes impurities from the torus exhaust gas and that separates the hydrogen species by e.g. cryogenic distillation or permeation systems [47]. The tritium plant has to process the whole gas flow coming from the torus pumping system and will thus be a large facility with a correspondingly high tritium inventory (approx. 5 kilogram [8]). Main reason for this large tritium inventory is the use of cryogenic distillation for isotope separation, what requires large distillation columns.

This tritium plant can most probably not be up-scaled towards DEMO, mainly for safety and licencing issues and for tritium availability reasons (there must be enough tritium in the world to provide the start-up inventory). Also economic reasons play an important role, as the market price of tritium is in the order of 20’000 Euros per gram [8], with a raising tendency as the supply situation gets worse. Reducing the tritium inventory is thus of prime importance for the design of a fusion fuel cycle, including tritium plant and pumping system.

The inventory in the tritium plant can be reduced mainly by two methods, namely (i) the change from cryogenic distillation towards other isotope separation techniques and (ii) the reduction of the throughput of the tritium plant. In view of throughput, it has to be kept in mind that the need for pumping in fusion reactors comes from the requirement to keep the helium content in the plasma low, below some few percent; otherwise the fusion power will be reduced strongly and the machine does not work economically anymore. Therefore, a large flow of pure fuel has to be injected into the plasma and pumped out again by the torus pumping system. By this process, helium is purged out constantly, together with more than 95 % of unburned fuel.

If it would be possible to recycle a large quantity of unburned fuel close to the machine, by passing the tritium plant and thus reducing the throughput, this facility would be much smaller with a corresponding lower tritium inventory. It must be noted that most of the tritium inventory in fusion reactors is not in the torus or in the pumps, especially when using continuously working pumps, but in the tritium plant.

As now a method for the separation of the torus exhaust gas directly in the primary pumping system is available (metal foil pumping), this can be used to realize this process: pure fuel can be separated from the exhaust gas and directly recycled to the torus via the fuel injection systems. This direct recycling close to the machine gives this new concept its name: *Direct internal Recycling* (DIR). This concept has also been developed during this work and is now under validation. DIR is seen as one crucial system for the realization of a power plant, as it is a tool to prevent the overall tritium inventory reaching unrealistic values.

4.7 Proposal of a novel vacuum pumping concept

Based on the combination of the DIR concept with the vacuum pumping methods identified before, a new vacuum pumping concept can be derived that leads to a strong reduction of the overall tritium inventory in the fuel cycle:

A gas separation is done in a very first pumping step close to the machine, using metal foil pumping. Here, only the hydrogen is compressed (i.e. pumped), not helium or other impurities. A second primary pumping method is thus needed to provide compression for these gas species. Here, vapour diffusion pumping is the first choice. Also for the pure fuel flow (i.e. the hydrogen gas coming from metal foil pumping), primary pumping is most likely required as metal foil pumping will probably not be able to work under the vacuum conditions provided by the rough pumping system only. For rough pumping, liquid ring pumping will be used. As working fluid for primary and rough pumping, mercury will be applied as it is fully tritium compatible and it will not be activated by neutronic radiation. Fig. 25 gives an overview on the Direct Internal Recycling (DIR) concept developed by KIT [48].

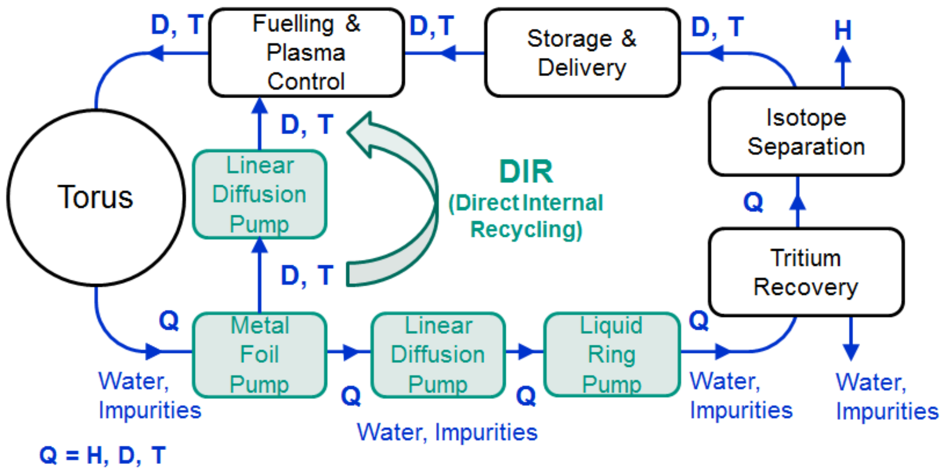


Fig. 25: Block diagram of the inner fuel cycle with Direct Internal Recycling (DIR).

5. Validation of the novel vacuum pumping concept

5.1 Description of the general approach

As the novel pumping concept proposed in the chapter before has never been demonstrated in experiments, the design choice has to be consolidated before it can be customized to a fusion reactor and a detailed design can be developed. Therefore, a literature survey has been done for each identified pumping method to find out if sufficient information is available. If gaps or unknown issues are found, this has to be identified and proof-of-principle testing has to be done to obtain the required information and to confirm the pumping method choice. Afterwards, the detailed design phase can start.

5.2 Literature survey on the pumping methods

5.2.1 Metal foil pumping

Pumps based on the physics principle of superpermeability do not exist on the market so far. Up to now, only theoretical and some small-scale experiments have been done in the lab to study this effect [e.g. 19, 46 – 57]. To find out if this method can be used for a DEMO pumping, a literature survey has to be done. Here, special focus has to be on the following aspects:

- Pressure range that has been investigated
- Particle flux achieved through the metal foil
- Method used for atomic hydrogen generation

The result of an extensive literature study is shown appendix A1. As major conclusion the survey illustrates that calculations or performance predictions cannot be done without results obtained by experiments.

The effect of superpermeability can be described as follows: The metal foil acts as a trap for atomic hydrogen with an energy exceeding 1eV [49]. This energetic hydrogen has to be provided by a source, applying hot rods or plasma atomizing methods. Once the hydrogen is absorbed by the foil, the hydrogen atoms will oscillate in the bulk material between upstream and downstream surface by random diffusion, leading to an increase of hydrogen concentration in the metal foil. Along the way, the dissolved atoms cool down, recombine with other hydrogen atoms and leave the isotropic metal foil to the upstream or downstream side with the same probability. (Isotropy describes the state of a metal foil, when the properties of the impurity layer, i.e. surface occupation, composition, thickness etc., are equal on the up- and downstream surface.) The low energetic hydrogen leaving the upstream side of the foil is energized again, allowing the atoms to enter the foil again, whereas for the gas leaving the downstream side of the foil, this is not the case. This is the reason for the compression by orders of magnitude that can be achieved with a metal foil in combination with a source of energetic hydrogen.

In total, superpermeation consists of the following steps:

1. Dissociation of hydrogen molecules into atoms
2. Physical adsorption of hydrogen atoms on the foil surface
3. Transition of hydrogen atoms to the metal lattice
4. Diffusion of hydrogen in the bulk metal
5. Transfer of hydrogen atoms to the rear surface of the foil

6. Recombination of the atoms on the rear surface
7. Desorption of hydrogen molecules

The driving force for superpermeability is thus a gradient in energetic hydrogen concentration – not in pressure – what makes the name super*permeation* misleading.

5.2.2 Vapour diffusion pumping

In view of vapour diffusion pumping, no well-characterized pumps in the pressure and throughput regime of interest and with mercury as working fluid exist on the market. Also here, a calculation of the pump performance ab initio is difficult, though the first concept to calculate the pumping speed of diffusion pumps was already developed by Wolfgang Gaede in 1915 [17]. The basic working principle behind his diffusion pumping theory is illustrated in Fig. 26.

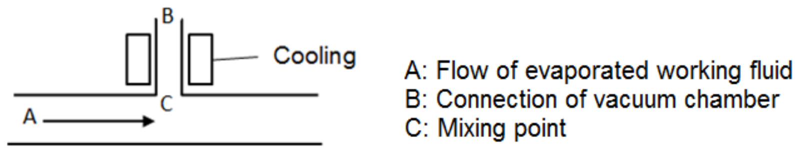


Fig. 26: Basic working principle of the diffusion pump by W. Gaede.

The chamber that has to be evacuated is connected via tube B. The evaporated working fluid flows through pipe A in the indicated direction. At point C, some vapour molecules enter tube B, but are condensed immediately due to the attached cooling system (e.g. by a cooling water jacket). The gas in the chamber flows through the tube B towards point C, where it enters the vapour stream and is transported away. In [17] Gaede states that the radius of B has to be smaller than the mean free path λ, that describes the average distance a molecule moves before it interacts with another particle, to avoid large amounts of vapour going into tube B. A sketch of his pump – the very first diffusion pump in the world – is shown in Fig. 27. In this set-up, he arranged the components as explained in Fig. 28.

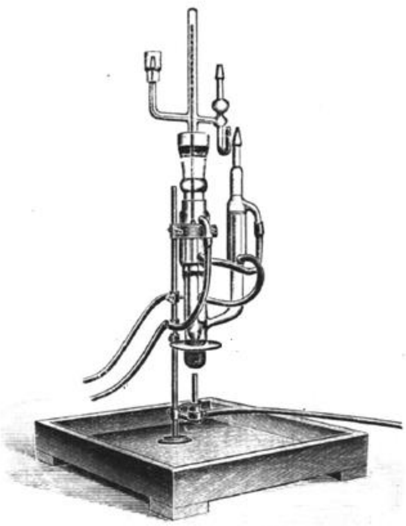


Fig. 27: Sketch of the first diffusion pump by Wolfgang Gaede [17].

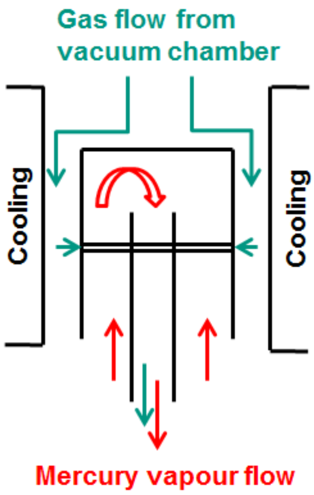


Fig. 28: Working principle of Gaede diffusion pump: The pumped gas (green) comes from a vacuum chamber located above and enters the mercury vapour flow (red) through a narrow slit into a cylindrical arrangement of two concentric pipes through which the mercury vapour is flowing.

A lot of (old) literature exists that tries to describe diffusion pumps: In [58] a general introduction on the topic of diffusion pumps is given, including calculation principles of the pump. The chapter on diffusion pumps was originally written by H. G. Nöller and carried on onto the ninth edition with only minor changes. The book is named after Max Wutz, who wrote the book *Molekularkinetische Deutung der Wirkungsweise von Diffusionspumpen* [59] which is a very sophisticated description of diffusion pumps, which can conclude from the geometry of a pump on its pump performance characteristics.

A good overview on the theory of performance calculations for diffusion pumps was also published by G. Tóth [60]. It describes the basic principle by Gaede [17] and the improvements by various authors like Jaeckel [61], Nöller [62] and Flourescou [63]. Tóth starts in 1967 by explaining the changes in diffusion pump theory over time and finishes with an own way to describe the diffusion pump mathematically. In the following years, Tóth adds five more papers about the theory of diffusion pumps. In each of these papers he has a certain sub-topic. In [64] Tóth calculates the ultimate pressure and the compression ratio of a diffusion pump. The third paper [65], which is very detailed, explains how the pumping speed can be calculated. In [66] a numerical solution for the equations presented in the former papers is given. In the fifth paper of the series [67] the methods of the earlier papers are used on a multi-stage model for diffusion pumps. In the last of the six papers [68], Tóth applies the theory behind his model on a two dimensional model. In all his theories, Tóth does not consider the flow rate of the working fluid vapour, which can be seen as the biggest disadvantage.

Since a higher computing power is available nowadays, a few new approaches towards the description of diffusion pumps has been done. In [69] a diffusion pump is simulated based on a Direct Simulation Monte Carlo (DSMC) approach. DSMC is a statistical approach based on particle tracking for high numbers of particles which travel through a given geometry. Most new papers on computational approaches to describe the diffusion pump come from the *Institute of Thermophysics* in Novosibirsk such as [70] or [71].

5.2.3 Liquid ring pumping

The performance of liquid ring pumps can be calculated analytically when assuming some simplifications:

- No evaporation of the working fluid
- No reduction of the cell volume by drops, foam or bubbles
- Cells are ideally tightened against each other
- Gas is treated as ideal gas
- No effects considered due to limited time for gas inlet or gas outlet
- Ideal geometries assumed for pump and liquid ring
- No condensation inside the pump, no solubility of gas in the liquid ring

All these assumptions show how simplified this performance calculation is. However, a physically correct description of all effects is very difficult, if not impossible. If this can be done at all, a fluid dynamic simulation program like ANSYS is needed. But simulating rotating geometries interlinked with multi-fluid and highly turbulent flows and complex physical boundary conditions is an extremely difficult task and a long-term effort. This is most probably the reason why a detailed performance calculation was never been done as the design has been evolved over decades by sound engineering practice in a number of commercial companies all over the world.

A calculation, assuming all the simplifications described above, is done in [72] and gives a good overview on this method. The influence of the working fluid in view of viscosity, surface tension or partial pressure is described by simple correlations in [73].

5.3 Experimental work

5.3.1 Experimental requirements

Metal foil pumping

The development status of metal foil pumps is very low; no pump based on this working principle has ever been built in a technically relevant scale. No information on the pumping behaviour under fusion relevant conditions (operation at pressures between 1 and 10 Pa), for different metal foils and with milder, plasma-based atomizing methods are available. A very basic proof-of-principle approach has thus to be done as a first step before the development of a real pump, able to operate under fusion relevant conditions, can be started.

For proof-of-principle testing, an experimental set-up is needed versatile enough to allow parametric studies, like the investigation of different metal foil materials and –thicknesses at different temperatures and with different gases. To keep costs for the experiments low, a facility in laboratory scale is desirable. This experimental set-up shall provide a vacuum during operation of up to 10 Pa and a plasma source that can be changed easily if necessary. It should also be possible to change the foil easily for experiments and to measure the permeation through the foil.

Vapour diffusion pumping

Though vapour diffusion pumps are available on the market for almost hundred years, it is impossible to find information on the operational behaviour of mercury diffusion pumps, combined with ejector stages in a fusion relevant throughput- and pressure range. One reason for that might be the fact that mercury as working fluid has been replaced by oil more than 50 years ago. It seems that the test results for such pumps – if they existed at all – have not survived.

However, these information are essential for considering this pumping concept for fusion power plants seriously. Proof-of-principle testing for the validation of diffusion pumping in fusion relevant pressure ranges is important before further efforts like simulation code- or prototype pump developments are undertaken.

Liquid ring pumping

Also liquid ring pumps exist on the market since a very long time. They are used under rough operating conditions in the chemical industry since decades. As far as we know, working fluids with a density considerably higher than the one of water have never been used for liquid ring pumping and thus no experience on the pump behaviour and the achievable pressures with such a high-density fluid is available.

Even if this seems to be only a mechanical problem, the (expensive) development of fusion relevant, i.e. fully tritium compatible, liquid ring pump at industry is a high risk without having demonstrated pump operation with mercury as working fluid in a proof-of-principle test first.

Considering these experimental requirements one can come to the conclusion that two experimental arrangements are needed: One small (laboratory-scale) facility for the demonstration of metal foil pumping and another facility for the demonstration/investigation of vapour diffusion- and liquid ring pumping with mercury as working fluid. Two facilities are needed as two completely different functions have to be realized: Firstly, permeation measurements through a metal foil using plasma and, secondly, vacuum pump characterization of different vacuum pumps using mercury as working fluid. Whereas the permeation measurements should be done in laboratory scale, the experimental facility for vacuum pump characterization must be large enough to test a liquid ring pump in a DEMO relevant design. For this theses, both facilities have been set-up and used for experiments: the HERMES facility was used for metal foil proof-of-principle testing and the THESEUS facility was used for proof-of-principle experiments with mercury diffusion pumps and mercury containing liquid ring pumps.

5.3.2 The HERMES facility

Primary aim of the HERMES experiment (acronym for: Hydrogen Experiment for Research of Metal foils and Superpermeability) is the demonstration of superpermeability with metal foils by using RF plasma. The experiment is designed in such a way that it is versatile enough to study superpermeability in a parametric way. It allows the measurement of the pumping speed and the compression level of different gas species, ion energies and materials, temperatures and foil thicknesses. It is expected to use the HERMES experiment intensively in the next years to generate a full database which can be used in the conceptual- and detailed design phase for metal foil pumps.

In HERMES, two chambers are segregated by a metal foil as shown in Fig. 29. In the upstream chamber, microwave excited hydrogen plasma is ignited to generated energetic hydrogen that can pass the metal foil. As consequence, a pressure rise in the downstream chamber can be measured. As the volume of this chamber is known, this allows the calculation of the throughput trough the foil.

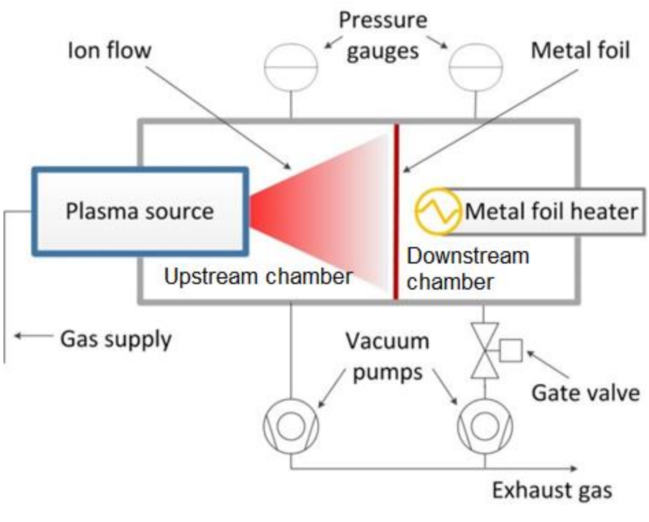


Fig. 29: Basic set-up of the HERMES experiment with their major components.

The metal foil, as heart of the experiment, is installed in an easily removable adaptor between the two vacuum chambers. The downstream chamber contains an electric heater to set a foil temperature between ambient and 600°C, whereas the upstream chamber contains the plasma source as source for energetic hydrogen. Both chambers are mounted on Bosch profiles on top of a base frame which also houses all infrastructure required for operation. A photograph of the experiment is shown in Fig. 30. All mayor components are described in more detail below.

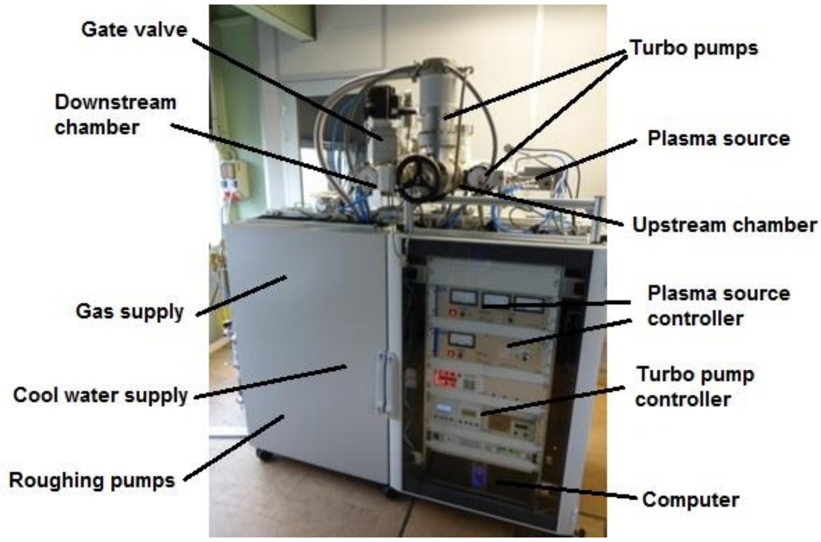


Fig. 30: Photograph of HERMES.

The vacuum for the upstream chamber is provided by two turbomolecular pumps (P1 and P2 in the flowchart shown in Fig. 31), backed up by the scroll pump P4 (by EDWARDS) for rough pumping. The two pumps are necessary for differential pumping of the plasma source: If the pressure in the back-part of the source becomes too high, plasma is ignited in this part and would cause a leak on the source. A third turbomolecular pump P3 is placed on the downstream side which is backed by the membrane pump P5 (by Vacubrandt). For the pressure measurement in the chambers and in the foreline, six gauges are mounted on the experiment: Two pressure gauges are placed on each up- and downstream chamber (P1, P2 and P3, P4) to be able to measure a wide pressure range (MKS Baratron capacity diaphragm gauges, Type 627, with 0.02 to 760 Torr measuring range and MKS Penning/Pirani combination gauges, Type 972B DualMag, that measure from ambient pressure down to 10^{-8} mbar). The foreline pressures of the turbo pumps are monitored by two EDWARDS Pirani gauges (P5, P6). For measuring the pressure rise in the downstream chamber (which is the information required to calculate the metal foil throughput), the pumping procedure has to be stopped. Therefore, the pump P3 can be shut off by the gate valve V5. This gate valve (by VAT) works pneumatically and closes in less than one second. This valve should not be operated at a pressure difference higher than 30 mbar to avoid damage. Therefore, a shortcut valve V4 was installed between upstream- and downstream chamber that tolerates up to two bar pressure difference. For conditioning the chambers (to reach low outgassing rates by removing water on the stainless steel surface), they can be baked out at 120°C. Therefore, four heating wires H1 – H4 (by Hillesheim) are wrapped around the chambers. An additional heater H6 is placed inside the electropolished downstream chamber to heat the metal foil via thermal radiation. H5 heats the adaptor flange (see below). On seven positions (T1 – T7) on the chambers, the temperature is measured by thermocouples Type K to regulate the heaters and to protect critical components from damage due to overheating (e.g. the VAT valve that can only be heated up to 120°C).

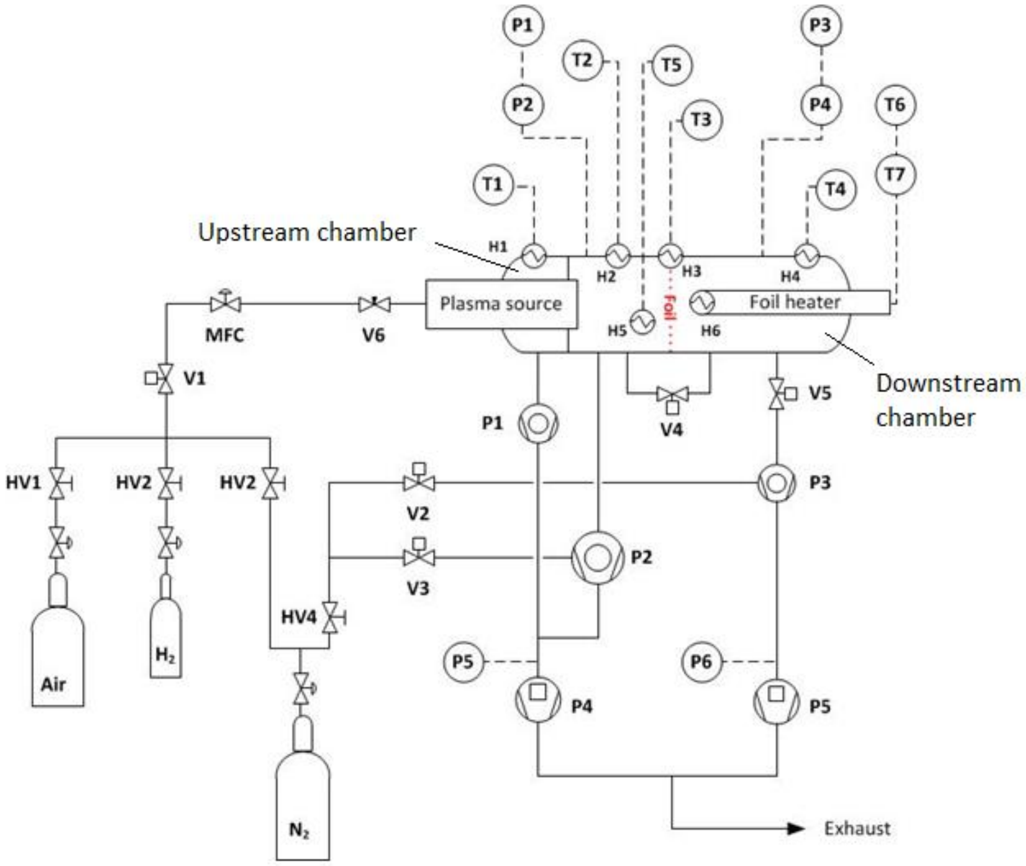


Fig. 31: Block diagram of the functional and operational equipment of the HERMES experiment.

The connection between the up- and downstream chamber is done by the foil adapter (Fig. 32). It consists of two parts with one side containing an all-metal (Helicoflex®) seal. The foil is clamped between this seal and the second adapter part (with smooth surface). This seal has a soft metallic hull – in our case Aluminium – with a spiral spring inside. The spiral spring generates a strong local compression and thus a high tightness. It can withstand temperatures up to 130°C and does not destroy the metal foil as it would be the case for CF flanges with sharp knife edges. Whereas most of the heaters on the experiment are controlled via the control system by a 2-point-controller, the metal foil heater H6 is supplied by a DC power supply (by HEIDEN, 0…60 V, 600 W) that is controlled via a 0…10 V input signal (scaled to 0…100% of output voltage) via the main control system. This guarantees a very accurate temperature control with a deviation of less than 1°C between ambient temperature and 600°C.

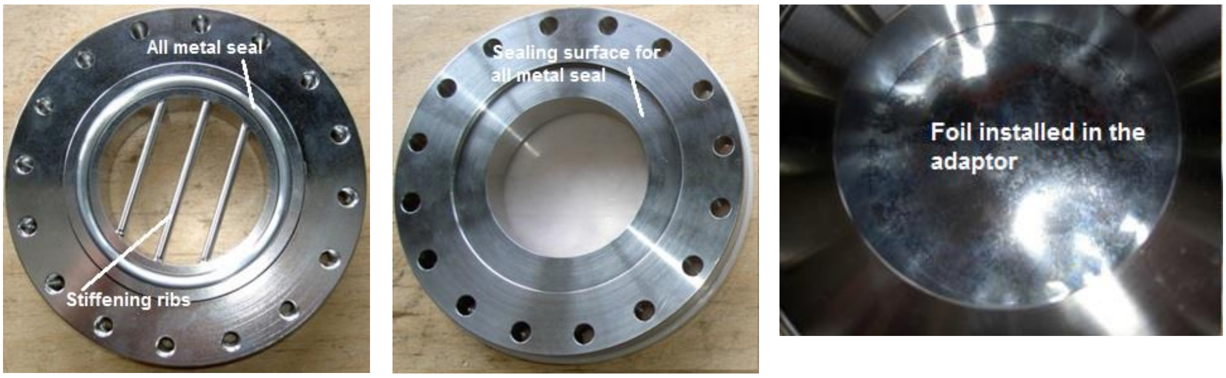


Fig. 32: The metal foil installed in the adaptor.

The plasma source (Fig. 33) is mounted on the upstream chamber and points directly to the metal foil that is located in front of the source in a distance of 50 mm. The source is a commercially available, linear plasma source (Gen II by TecTra) that contains a 250 W water cooled 2.45 GHz magnetron. The microwaves are transferred to a ceramic cup installed in the tip of the plasma source via a 300 mm tungsten slab. Into this cup, the gas in injected and immediately ionized by the radio frequency. For higher ionization efficiency, the ion cyclotron resonance heating effect is applied. This requires (water cooled) magnets around this cup. Two grids in front of the cup can be supplied by a high positive or negative voltage: The positive voltage holds the low energetic particles back in the cup and allows thus the adjustment of the ion energy, whereas the negative voltage leads to a more focused beam due to a strong extraction and acceleration of the ions.

The infrastructure required for the experiment is housed in the Rittal base frame (1200 mm high, 800 mm deep and 1600 mm long). The gas bottles for the experiment are attached from outside to the frame: Two 200 bar, 10L bottles (nitrogen and synthetic air). Pressure reducing valves are installed directly on the bottles to reach a working pressure suitable for the mass flow controller (0.5 bar(g)). Protium and deuterium for the plasma source is provided by 1 litre, 12 bar pressure cups (by Air Liquid). In the left side (see Fig. 30) of the base frame, a chiller for cool water supply (by Huber) and the two rough pumps (EDWARDS and Vacubrandt) are located. Also the mass flow controller (by MKS Type MFC, Type MF1, max. flow range 10 sccm nitrogen equivalent), the cool water distribution system and control/electronic system is located there. The right side of the base frame is equipped with a 19” rack, where all controllers and power supplies and the computer for control and data acquisition are installed.

The experiment is controlled by a Siemens Programmable Logic Controller (PLC) system (SIEMATIC S7) in combination with a ProfiMessage data acquisition device (by Delphin Technology). The operation can be done fully remotely from an operator place close by, where the control software (Siemens WinCC) and the data acquisition software (ProfiSignal by Delphin Technology) can be followed on two screens. The PLC controls the plasma source, the heaters, the pumps and ensures that no (hydrogen-) overpressure in the vacuum chambers can occur (i.e. no gas dosing at a pressure higher than 100 Pa).

HERMES has been commissioned with nitrogen to demonstrate that the whole set-up incl. the plasma source works well. With a gas flow of 10 sccm to the plasma generator, a pressure of $4 \cdot 10^{-2}$ Pa is reached in the upstream chamber. At about 35% magnetron power, the plasma ignites. The colour is bright violet and becomes more shining with increasing power. During this first commissioning phase of the experiment, the downstream chamber is still not installed and the plasma faced a blind flange. Using synthetic air for plasma operation does not have an influence on the plasma performance; only the colour changed as oxygen plasma is blue. For hydrogen plasma, also used in this commissioning phase, the performance is different: Hydrogen is more difficult to pump by kinetic (in our case: turbomolecular) pumps. A gas flow of 10 sccm results in a pressure of 0.1 Pa. At this value, a plasma ignition is not possible. Only when using a nitrogen plasma first and changing the gas to hydrogen during the experiment, a plasma operation is possible up to 2 Pa (Fig. 34). High pressure values in HERMES are desirable as this means also a high particle flux to the foil and thus a strong permeation effect of the foil.

The HERMES experiment has been designed, set-up and commissioned during this work and used for metal foil pumping proof-of-principle testing (see chapter 5.4.1).

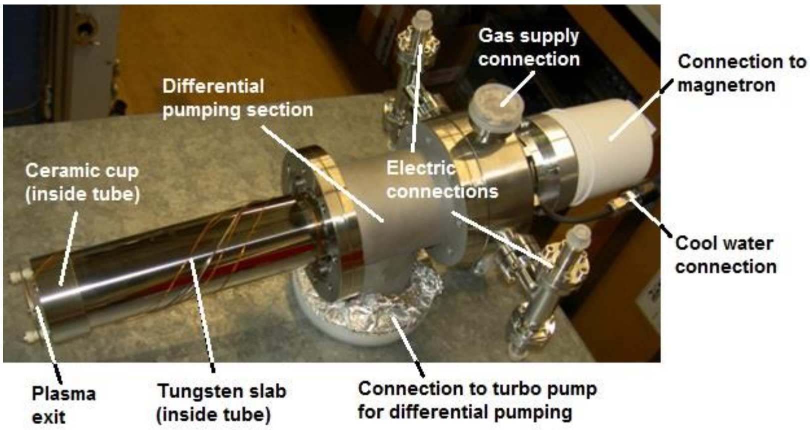


Fig. 33: The Gen II Plasma Source by TecTra. The magnetron is installed on the right, in the middle the differential pumping stage and on the left the exit of the source.

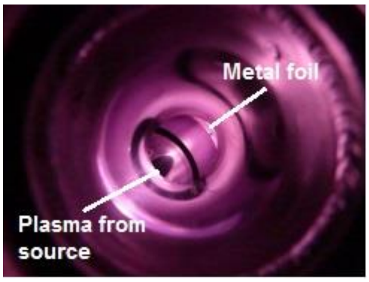


Fig. 34: Hydrogen plasma in HERMES at 2 Pa, observed through the viewport on the upstream chamber.

5.3.3 The THESEUS facility

The THESEUS facility shall become the central test environment for DEMO relevant vacuum pumps, primary pumps as well as roughing pumps. Therefore, a recipient is needed, where test pumps can be installed and information on pumping speed, foreline resistance, throughput and ultimate vacuum can be obtained. As the pumps can be based on vapour diffusion- or liquid ring pumping, it is mandatory to cover a wide pressure range with this facility. Also the use of different gases under DEMO relevant conditions must be possible. Due to potential hydrogen experiments and experiments with mercury, the required framework (e.g. a safety system for hydrogen operation, a mercury analysing system) has to be provided in THESEUS.

For liquid ring pumping experiments, a liquid ring pump has to be installed in a DEMO relevant design. As these pumps are typically very large pumps with a high throughput, it is expected that also the pump to be installed in THESEUS is relatively large. This defines the size of the facility: It consists of a platform with a footprint of approx. 10 x 10 meter. The upper and the lower part is shown in Fig. 35 and Fig. 36, respectively.

Fig. 35: Upper level of THESEUS: The control room in the background, the gas dosing system in front and the dosing dome with the box for the pressure measurement equipment in the middle.

Fig. 36: Lower level: The liquid ring pump is located in the housing on the right; the connection to the dosing dome can be seen in the middle. On the left the board for the gas analysing and mercury tracking systems.

The upper part of THESEUS contains the infrastructure systems (chiller for cool water supply, gas dosing system, service vacuum pump, power supply, cubicles), the control room and – as central part of the facility – a dosing dome used as recipient. The lower part of the facility is reserved for the pumps and the mercury vapour monitoring system. Pumps can be connected directly to the dosing dome via two test ports (DN200CF and DN300CF). The dosing dome can be baked out at 200°C using a 7.5 kW electrical heating system, consisting of eight heating circuits (Fig. 37). The dome can be evacuated by a large, two stage rotary vane pump (Pfeiffer DUO 128 m^3/h) as service vacuum pump to a pressure down to 0.1 Pa. The dosing dome is required to guarantee a uniform pressure distribution at the pump inlet. It is built according to European standards [74] and can resist a gauge pressure of 1 MPa. The shock resistant design is TÜV approved and required for the safety concept described below.

The dosing system allows the injection of gas at a known and adjustable flow rate into the dosing dome. For adjusting a gas flow, two sets of mass flow controllers (MFC; by MKS Type 1259) are available: The first set comprises four MFCs (0.1, 1, 10, 20 standard litre per minute (slm) maximum dosing rate) and one mass flow meter (200 slm maximum measuring rate) with an upstream hand valve. The second set of MFCs comprises three MFCs with a maximum dosing rate of 0.5, 10, 100 standard cubic centimetres per minute (sccm) and one MFC with 1 slm. All MFCs can operate between 2 and 100% maximum dosing rate. The error of the devices as given by the manufacturer is better than 2% of reading.

The dosing system can be operated in two modes: It allows a closed cycle operation for the process gas, where the pumped gas is recycled again to the dosing dome, or an open cycle operation mode, where gas from the local gas storage outside the building is dosed into the dosing dome and pumped out via the test pumps without recycling. Also a hybrid mode can be realized where one part of the pumped gas is recycled with the second set of MFCs whereas the first set of MFCs allows increasing or decreasing the total gas inventory in THESEUS with gas from storage. All MFCs work with two 0-5 V signals (scaled linearly to the full range of the device): One for setting a flow and a second one for reading back the actual value. The whole board is kept at a constant temperature of 25°C to guarantee a stable operation of the MFCs, independent of the ambient conditions in the experimental hall. The gas flow through the dosing system is guided by a number of pneumatic valves that are controlled by a pneumatic valve cluster located in the nearby cubicle that is connected to the main control system. The valve position information is looped back for a proper error analysis in case of a failure. The whole gas dosing system is located in a board (Fig. 38) next to the dosing dome.

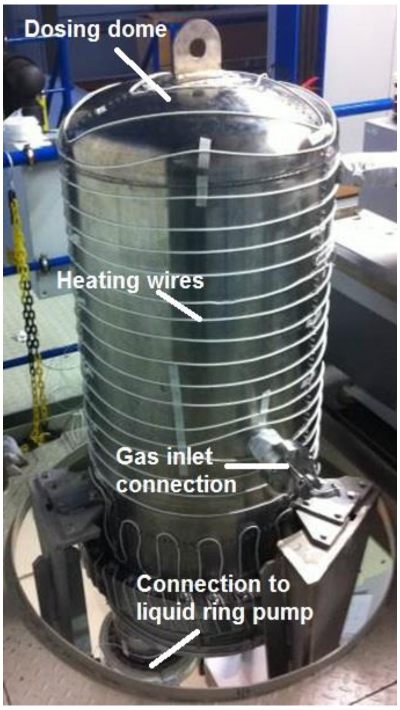


Fig. 37: The dosing dome without insulation during set-up.

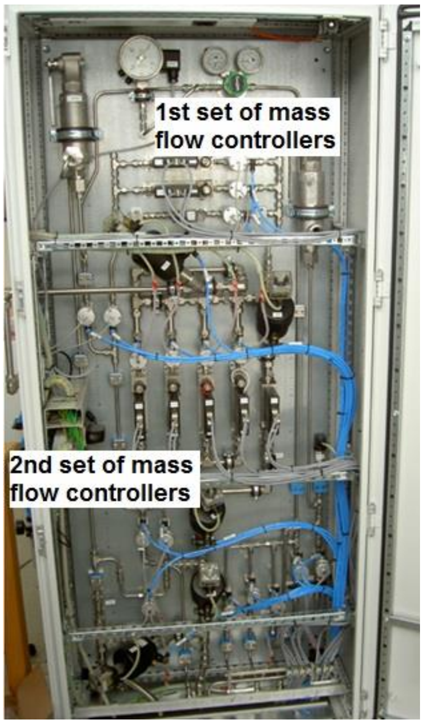


Fig. 38: The dosing system with two sets of MFCs.

The pressure in the dome is measured by two capacitance diaphragm gauges (by MKS, Type Baratron 470) that can measure between 10^{-2} and 100 Pa and 10 and 10^{5} Pa, respectively. The accuracy of these devices is 0.08 % of reading and may further be improved by regular calibrations. For pressures below the lower limit of the capacitance gauges, a hot cathode ionization gauge (Leybold ITR100) is installed for pressure measurement down to 10^{-8} Pa. The accuracy of the device is approx. 5 % of reading. Knowing the dose rate Q in the dome and the pressure p, the pumping speed of the attached pumps can be calculated by Q/p.

For safety reasons (no people allowed in the facility during hydrogen experiments), THESEUS is a fully remote-controlled test facility. All experiments will be performed remote operated from a control room via a Supervised Control and Data Acquisition system (SCADA). The heart of this system is a commonly used programmable logic controller (SIEMATIC S7 by Siemens) connected via a bus system (Profibus®) to the different components inside the facility (e.g. frequency transformers, flow meters, analogue or digital input- and output stations, etc.). As graphical user interface, the WinCC software (by Siemens) was chosen. All measuring points (mass flow controllers/meters, pressure gauges, temperature measurements etc.) in THESEUS are either connected directly to the S7 via analogue input or output cards or to the data acquisition system (TopMessage by Delphin Technology) from where the signals are transmitted to the S7 and WinCC via Profibus. The 23-bit TopMessage data acquisition device can be equipped with two measuring cards that allow the sampling of up to 30 measuring points per device with a sum sampling rate of up to 600 Hertz, depending on the installed measuring card. The TopMessage master device can be expanded with several slave stations connected via a two-wire CAN-bus. During experimental campaigns, two workstations in the control room with graphical user interface systems are used in parallel: The main control system (with the WinCC software), where the operator runs the experiments and the data acquisition system (with the ProfiSignal software by Delphin Technology) that is operated by the experimenter and that runs independently of the main control system.

In THESEUS, no experiments with tritium will be performed. However, experiments with hydrogen will be made and the results, if necessary, extrapolated to tritium. This is especially important for pumps that show a strong gas species dependency like kinetic- or vapour diffusion pumps. Hydrogen forms explosive gases with oxygen, if the vacuum part of the facility becomes leaky and air enters. If the hydrogen content in the facility exceeds 4 % and the total pressure 370 mbar, the oxy-hydrogen mixtures can be ignited [75]. The safety concept of THESEUS foresees three different methods of explosion protection:

- Explosion safety due to the avoidance of an explosive atmosphere (primary explosion protection) by regular checks for leak-tightness and the installation of hydrogen sensors in the experimental hall.
- Explosion safety due to the avoidance of an ignition (secondary explosion protection) by avoiding any (active) sources for ignition in the facility.
- Explosion safety due to the mitigation of the effects of an explosion (constructive explosion protection).

Constructive explosion protection in THESEUS means that the resulting pressure rise of a hydrogen explosion will not represent a hazard to the facility operators. This requires that all components in the facility being normally under vacuum conditions (e.g. the dosing dome) have to be designed and manufactured in a shock pressure resistant way [76]. All components that cannot be made shock pressure resistant (like e.g. vacuum gauges) must be protected by a casing to hold back dangerous loose parts in case of a burst. Shock pressure resistance denotes that plastic deformation is allowed in case of an explosion, but no burst. Moreover, the access to the facility will be prohibited during hydrogen experiments.

To ensure that the design pressure for the dosing dome of 10 bar(g) is not exceeded in case of an explosion, the hydrogen inventory available for experiments has to be limited by a safety relevant and reliable control system. The philosophy of this approach is illustrated in Fig. 39. The so-called *Hydrogen Interlock System* (HIS) limits the maximum available amount of hydrogen/deuterium for experiments to 140 litre (stp). This value is being calculated on a worst case basis, assuming that the whole amount of gas is in the dosing dome when air enters at such a pressure that the end pressure is maximized [77]. If an experiment with hydrogen shall be started, the facility including the test pump has to be evacuated to a good technical vacuum (pressure below 1.6 mbar, given by the lowest resolution of the used mechanical pressure switch). The evacuation status of the facility is then sent to an approved safety system that works independently from the THESEUS main control system. If now a confirmation button in the control room is pushed, an intermediate storage vessel is filled by the gas supply system to a pressure that defines the 140 litre. After filling, the intermediate storage is locked against further filling by two redundant valves, and, afterwards, connected to the gas dosing system by another valve. Now, experiments can be performed until the 140 litre vessel is empty. Then, the procedure described above can be restarted.

A photograph of the HIS is shown in Fig. 40. The mayor part of the system with its valves, intermediate storage vessel and pressure gauges is installed in the gas storage outside the building. As this location is defined as Ex Zone 2, all electrical components (like valves and gauges) have to be e.g. intrinsically safe and a large installation effort is required as all cabling has to be done in an appropriate way, using only certified components, cables and even cubicles and clamps.

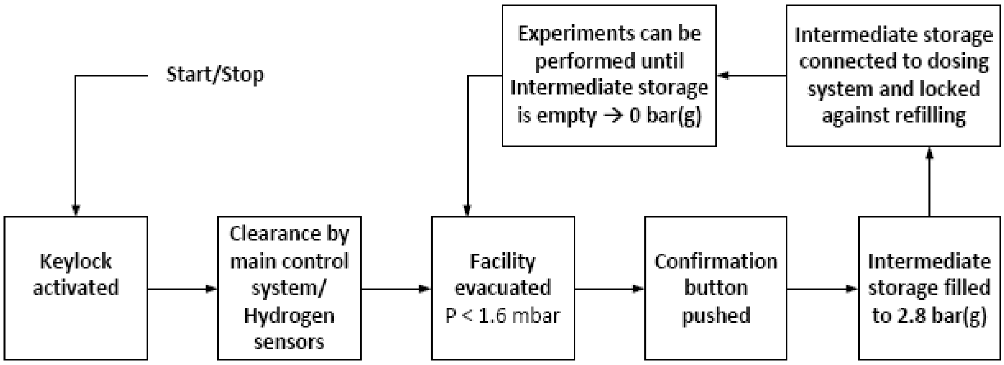


Fig. 39: Block diagram showing the working principle of the Hydrogen Interlock System.

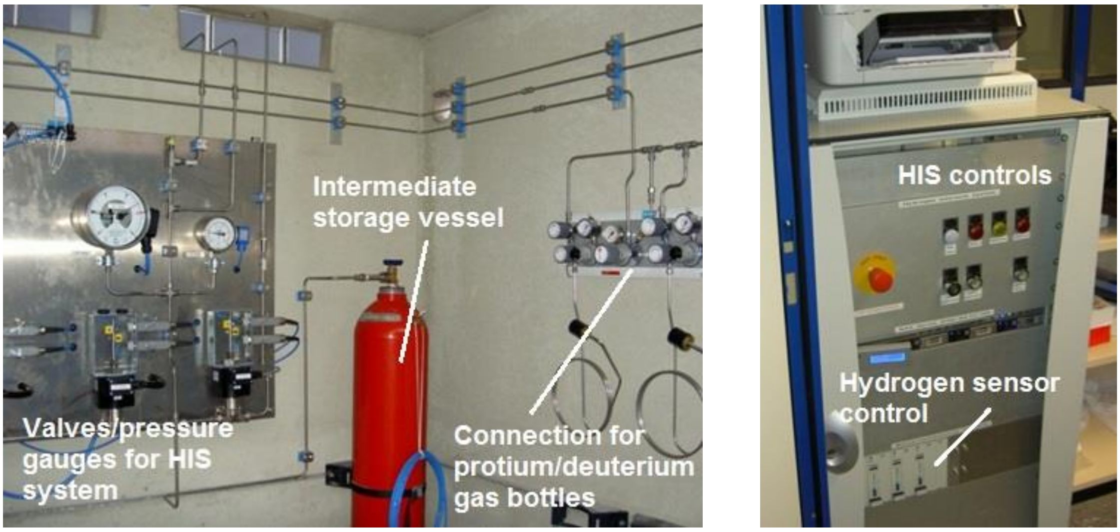


Fig. 40: The Hydrogen Interlock System (HIS): Left the installation in the gas storage and left the hard-wire controls in the control room.

Four hydrogen sensors are additionally connected to the safety system (main alarm if 40 % of the lower explosion limit is detected) and three emergency switches that will immediately stop hydrogen operation and evacuate the facility automatically by the service vacuum pump if an alarm is present. The Hydrogen interlock System has to be checked regularly and also the hydrogen sensors have to be calibrated regularly by the manufacturer. More detailed information on the set-up of the safety system can be found in [77].

For mercury vapour monitoring, an Atom Absorption Spectroscopy (AAS) (by Mercury Instruments, VM-3000 mercury quality monitor) with integrated membrane pump has been installed. It can be used at ambient pressure and is thus applicable only in the exhaust gas stream of backing pumps and for analysing ambient air. It has a measuring range of 100 to 0.1 ppm and is connected to the measuring points via a valve box. This valve box allows also the guiding of the AAS exhaust gas flow back to the process (closed circuit operation) or in the exhaust line of the facility. In total there are two measuring points foreseen for process monitoring and three for ambient monitoring. All electrical valves in the valve box are controlled via the THESEUS main control system. The piping has to be specially coated to ensure minimum mercury vapour surface adsorption.

Fig. 41 shows the working principle of an AAS: The gas that shall be analysed is pumped through an optical cell. In this cell, the mercury vapour is excited by a light beam with suitable wavelength coming from a UV lamp (mercury vapour lamp; excited by a high frequency (HF) generator). This means, the UV light beam going through the optical cell loses energy and is being weakened. This weakening is proportional to the mercury content in the cell and can be measured.

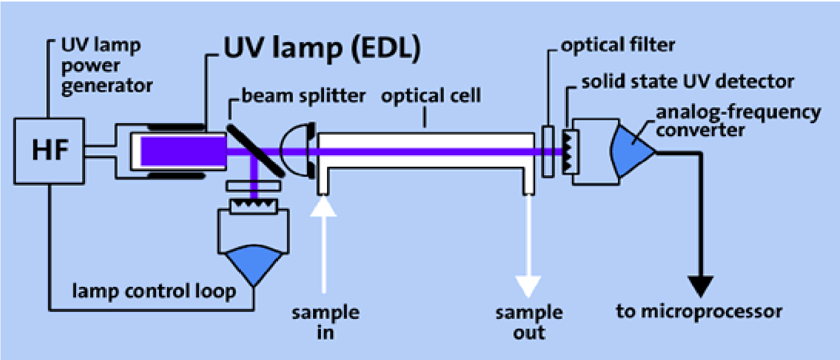


Fig. 41: Working principle of an Atom Adsorption Spectrometer. (Taken from www.mercury-instruments.com)

The THESEUS facility has been designed, assembled and commissioned during this work and used for diffusion pumping- and liquid ring pumping experiments (see chapters 5.4.2 and 5.4.3). A detailed flowchart of the facility can be found in appendix A2 and shows the complexity of the whole facility.

5.4 Proof-of-principle testing

5.4.1 Demonstration of superpermeability

After commissioning of HERMES, the facility has been used to demonstrate superpermeability with hydrogen plasma in a fusion reactor relevant pressure range (around 1 Pa).

As first step, the vacuum chambers have been baked out for two days at 120°C to remove water and solvents that may have remained in the system from cleaning. After cooling down to ambient temperature and setting the metal foil temperature to 300 °C, pumping has been stopped in the downstream chamber by closing the gate valve to the pump and the pressure rise in the downstream chamber has been recorded while the upstream chamber is still evacuated. During the first 14 minutes, the pressure has been too low to measure with the available gauges. Then the pressure started rising with a constant particle flow into the chamber of approx. 10^{13} particles per second. This is the integral value of outgassing and (potential) leaks.

In the second blind measurement, the metal foil has been heated again to 300°C and the upstream chamber pressure is set to approx. 1 Pa by setting the hydrogen gas flow to the plasma source to 10 sccm. At this state, stable hydrogen plasma is possible. However, the plasma has not been ignited so that only normal permeation effects can be detected. After closing the gate valve, it takes over 24 minutes until the pressure is high enough to be measured. The calculated particle flow is again approx. 10^{13} particles per second. As this is in the same order of magnitude as the first blind measurement, this leads to the assumption that permeation effects through the hot metal foil are negligible.

In the next experiment, the plasma is ignited to demonstrate superpermeation. As the metal foil takes some time to be saturated with hydrogen, plasma is ignited for 1.5 hours at a pressure of 2 Pa before the experiment is started. Then, the gate valve (see Fig. 29) is closed and a pressure rise is observed after only 10 seconds. 12 minutes later, the pressure gauge reaches its upper limit (2.6 Pa). The resulting particle influx was $1.3 \cdot 10^{15}$ particles per second and the area specific pV-throughput can be estimated to $5.5 \cdot 10^{-6}$ Pa m³/m² s. These values are more than two decades larger than in the second blind measurement and demonstrates the effect of superpermeation. To ensure that the foil does not crack during the experiment, the plasma source is turned off and the gate valve is opened again. Nearly instantly the pressure dropped under the measurable pressure range. After closing the valve again, no significant pressure raise is measured, similar to in the first blind measurement, meaning the metal foil is still intact. The resulting pressure rise is shown in Fig. 42.

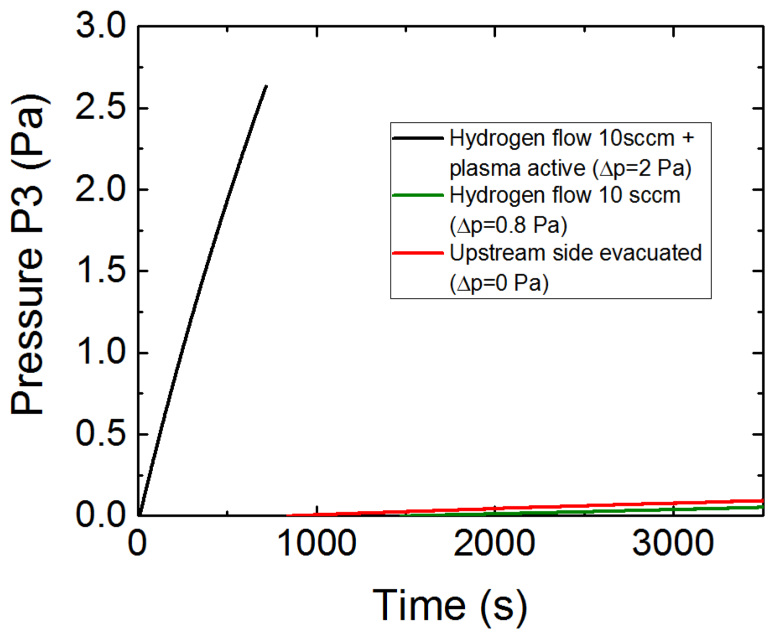


Fig. 42: Comparison of the two blind measurements (green and red) with the measurement with active hydrogen plasma (black).

5.4.2 High-throughput vapour diffusion pumping

Goal of this proof-of-principle experiment was the characterization of diffusion-ejector pumping at relatively high inlet pressures and the break-down behaviour when approaching the critical backing pressure. These information are essential for the operation of such a pumping system under DEMO relevant conditions.

For this experiment, an old (more than 50 years), small diffusion pump (Model EM2 by Edwards) with two diffusion stages and one ejector stage has been used. A cut-view of this pump is shown in Fig. 43, a photograph in Fig. 44. This pump has been used in a field ion microscope at the University of Graz, Austria, for several decades and showed an excellent reliability: During its operation time the heater plate of the pump has been replaced once; no other repairs are known. After about 30 years of service it has been replaced by a turbo pump due to its simpler operation (no liquid nitrogen baffle needed).

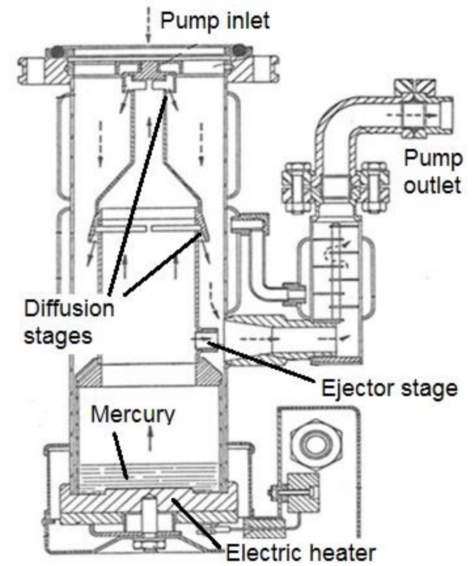


Fig. 43: Cut view of the EDWARDS EM2 diffusion pump [78].

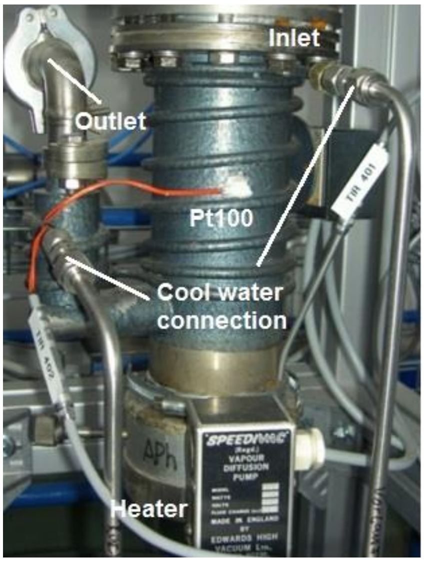


Fig. 44: Photograph of the EDWARDS EM2 mercury diffusion pump.

The pump is ideally operated with 75 ml of mercury but it is adaptive in the range of 50 – 100 ml. The pump consists of three compression stages, two stages with circular nozzles and one lateral injection nozzle into the exhaust stream. The mercury is electrically heated by a 350 W heater plate and cooled by approx. 0.4 l/min of 15°C water. In order to reach a higher vacuum than the vapour pressure of mercury (0.16 Pa at 20°C) a cooling baffle is installed between the vacuum chamber and the pump. The baffle is cooled with liquid nitrogen at 77 K. The pumping speed for air is given by the manufacturer with 150 l/s (without baffle, wall temperature 15°C) and the ultimate vacuum (with baffle) with 10^{-5} Pa [78].

The diffusion pump test campaigns have been performed in the initial stage of the THESEUS facility. At this stage, the large dosing dome and the gas dosing system as described in chapter 5.3.3 was not installed. The flowchart of this early set-up is shown in Fig. 45, a photograph of the set-up is shown in Fig. 46.

A gas dosing system is connected to the gas distributor where the gases helium, nitrogen or argon can be chosen by the hand valves HV1 to HV3. The dosing system consists of three mass-flow controllers MFC1 to MFC3 with maximum adjustable throughputs of 0.5 sccm (MFC1), 10 sccm (MFC2) and 100 sccm (MFC3), respectively. To regulate the flows, the controllers use an internal proportional valve, controlled by a PID controller. The flow is determined inside the mass flow controllers by measuring the pressure difference over a restriction in a tube (MFC1) or by measuring thermal losses of a heated wire (MFC2, MFC3). The gas is then released into a dosing dome B1 with a capacity of 23 l. This dome can be heated up to 200°C by heater H1 for conditioning (bake-out for water removal). Connected to this dome are three pressure gauges (P1 – P3) able to measure the pressure over a wide range. The two installed capacitive pressure gauges P1 and P2 (Type MKS Baratron) can operate in a pressure range from 1000 to 1 Torr and 1 to 10^{-3} Torr, respectively. The Bayard-Alpert hot ionisation gauge P3 (IONIVAC ITR100 by Leybold) can measure in the range of 10^{-8} to 0.1 Pa.

The diffusion pump P1 with upstream baffle is connected to the dosing dome via the DN63 gate valve (by VAT) V0. A bypass to the diffusion pump (via valve V9) allows the connection of the rotary vane backing pump P2 directly to the dosing dome. When the bypass is closed, the gas has to pass the inlet baffle (Edwards NTM2A) that is cooled by liquid nitrogen. If the baffle gets empty, this is indicated by a raise of temperature T2 and liquid nitrogen is filled in automatically via valve V6. Downstream the baffle, the pumped gas enters the mercury diffusion pump P1. The pump is cooled by a chilled water system to a temperature T3. For temperature measurement, a Pt100 resistance temperature sensor is used. The cold water is provided by the THESEUS 12 kW cooling plant. (This high cooling power is not needed for testing this pump, but it will be needed for the next expansion stages of THESEUS, e.g. the testing of the mercury ring pump.) The gas leaving P1 has to pass the backing pump P2, which is a two stage rotary vane pump (by Pfeiffer) with a nominal pumping speed of 128 m^3/h, before it is exhausted. To be able to measure the backing pressure of the diffusion pump, another MKS Baratron pressure gauge (P5) with a measuring range of 10 to 0.01 Torr is connected between the two pumps. For experiment control and data acquisition, the THESEUS SCADA system described before is available.

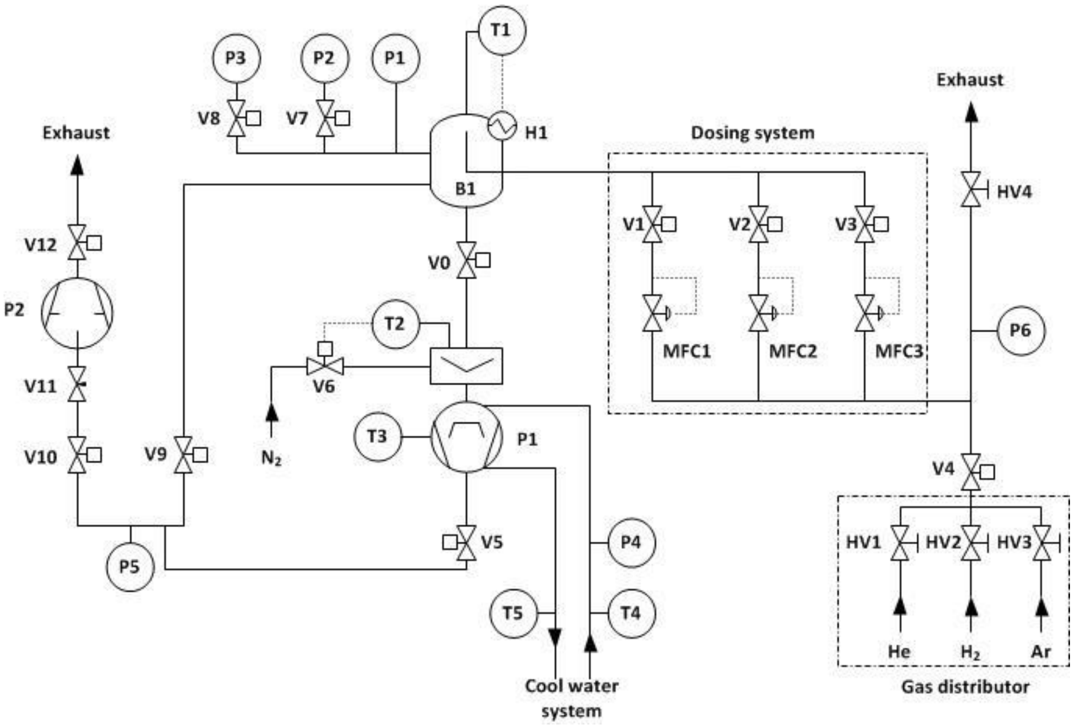


Fig. 45: The P&ID-diagram of the diffusion pump test set-up in THESEUS.

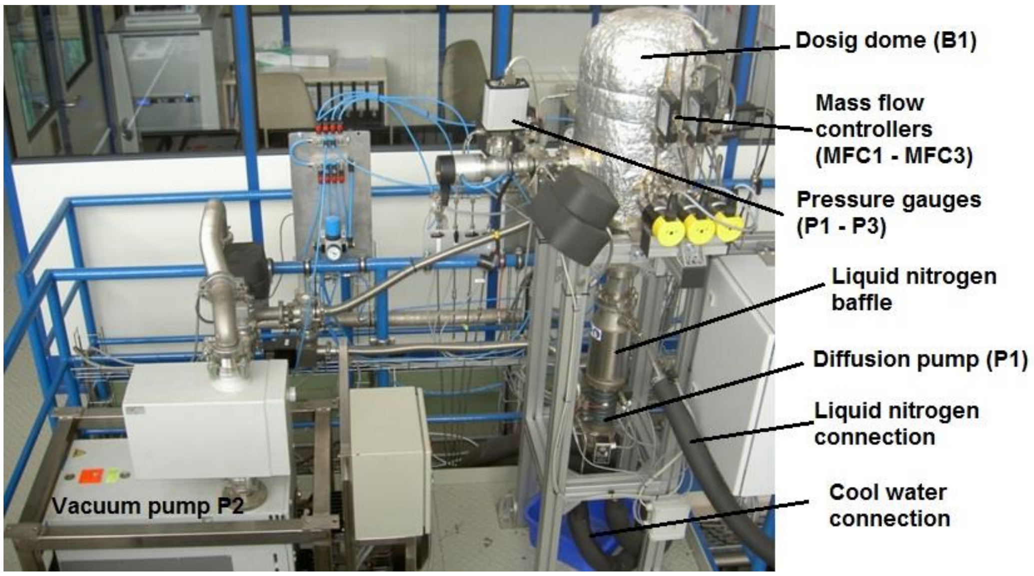


Fig. 46: Photograph of the diffusion pump test rig in THESEUS.

The pumping speed curve obtained by this experiment is shown in Fig. 47. Here, the pumping speed S is plotted as a function of the pump inlet pressure p. For each point of the graph, the gas flow into the dome has been adjusted via the MFCs while the diffusion pump is working. After some minutes, the pressure values in the dosing dome are constant. Then, the flow Q and inlet pressure data are taken over a time period of approximately five minutes. These values are averaged and the pumping speed is calculated by S = Q/p. All measurements has been performed for the gases helium, nitrogen and argon in a flow range varying from 0.01 to 10 sccm (nitrogen equivalent). The mass flow controllers have been calibrated to nitrogen; for measuring the other gases, the indicated gas flow has been corrected by the quotient of dynamic viscosities:

$$Q_i = Q_{N2} \cdot (\eta_2/\eta_i) \qquad (5.1)$$

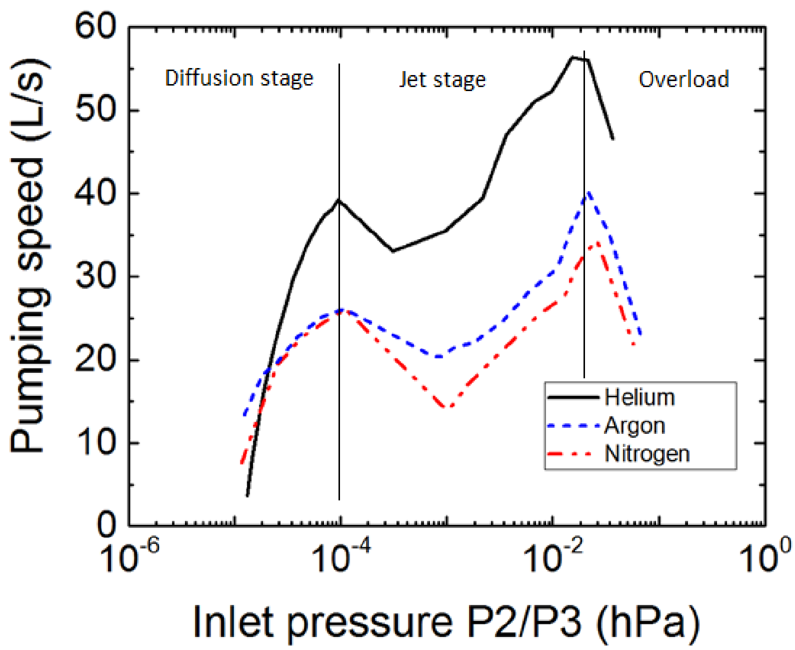


Fig. 47: Measured pumping speed curve for the mercury diffusion pump for different gases.

The measured pumping speed curves show clearly three operational regimes for diffusion-ejector pumping, namely the typical (diffusion-)pumping range, known from pure vapour diffusion pumps, the pumping regime given by the jet stage, and finally the overload regime at high pressures and throughputs. According expectation, helium has the highest pumping speed of the used gases with a peak at 42 l/s in the diffusion range. This means that the installed baffle reduced the theoretical pumping speed by approx. a factor of four (from 150 l/s). In the diffusion range, the differences in pumping speed between nitrogen and argon is neglectable, at higher pressures, the pump showed a better pumping behaviour for nitrogen. The gas species dependency can easily be explained by the working principle of the pump: The gas that shall be pumped diffuses into a jet gas flow and is then transported by momentum exchange. Light molecules diffuse much better than heavy molecules, what finally leads to a better pumping for light gas species. This effect is very advantageous for fusion applications where mainly deuterium and tritium has to be pumped. Hydrogen and hydrogen isotopes should have even higher pumping speeds, but at that time, experiments in THESEUS had not been possible for licencing reasons.

In order to identify the critical backing pressure, the inlet pressure dependency on the backing pressure has been measured. Therefore, a constant flow is set by the MFCs and the backing pump was disconnected slowly from the diffusion pump by closing valve V11. A rising backing pressure is now measured by P5 and the pump inlet pressure is measured by the pressure gauges P1 and P2, respectively. The value of the critical backing pressure is determined by the procedure given in the German norm DIN 28 427 [79]: The critical backing pressure is reached as soon as the backing pressure rise leads to an inlet pressure rise being 10% of the rise in backing pressure. Fig. 48 and Fig. 49 illustrate the relation between inlet and backing pressure for nitrogen (argon was very similar) and helium.

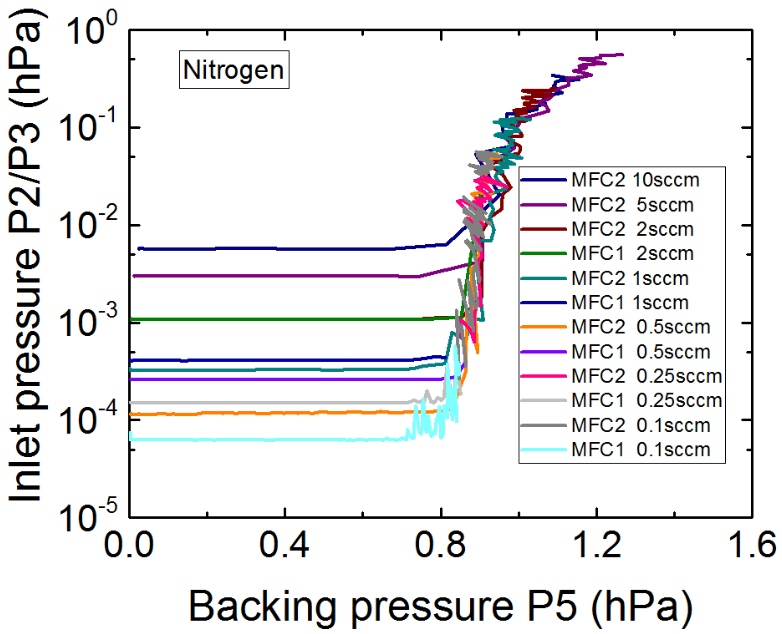


Fig. 48: Inlet pressure over backing pressure for nitrogen.

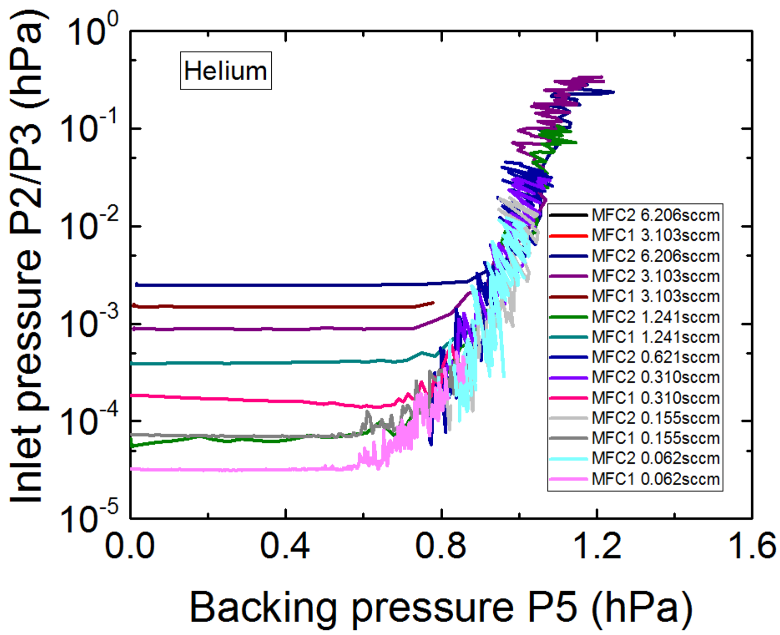


Fig. 49: Inlet pressure over backing pressure for helium.

It can be seen that the diffusion pump was able to keep the inlet pressure over a wide range of backing pressure constant. The shape of the inlet over backing pressure curves showed a similar behaviour over the full range of adjusted gas flows. At around 800 Pa, the pump finally collapses and the inlet pressure rises quickly to a high value. This pressure is in most cases about one tenth of the backing pressure. This shows that the compression ratio of the (still working ejector stage) must be about ten.

Although the curves for the gases nitrogen, argon and helium look similar, the helium curves show a modest raise of the inlet pressures before the pump breaks down. For light gases, the breakdown of the pump takes place at slightly higher backing pressures. This is in agreement with the higher compression for light gases. Argon and nitrogen have a sharper breakdown behaviour, but at lower absolute values. This can be explained by a back diffusion of the light molecules because of the pressure gradient through the mercury vapour rises. In [80] the diffusion coefficients of the system mercury-helium and mercury-nitrogen are measured, the diffusion coefficient for mercury-helium is four times as high as for mercury-nitrogen. In this case the diffusion behaviour of nitrogen is approximately the same as for argon [81]. This is the reason why this inlet pressure rise can only be observed in the measurements with helium. For a technical application, this behaviour is advantageous because it indicates a breakdown in advance and allows the operator or a safety system to react before pumping fails.

5.4.3 Liquid ring pumping with mercury as working fluid

Liquid ring pump proof-of-principle testing was done in the THESEUS facility, where an enclosure with the test pump has been installed right below the dosing dome. The enclosure is vented to remove any mercury vapours that may exit the pump train in case of a leak. The housing is 2.5 m long, 2 m high, 1 m width and accessible via doors from all sides. A water filled bowl below the pump (but inside the housing) guarantees that all mercury that may leave the pump in case of a leak is immediately covered with water to avoid the formation of toxic mercury vapours. Fig. 50 shows the liquid ring pump with the electric gear engine inside the enclosure.

After the gas in the dosing dome is being pumped out by the mercury ring pump, it enters the phase separator, where the mercury is separated from the processed gas. Assuming that the gas is loaded with mercury vapour, the mercury has now to be condensed or frozen out in the following 3-stage gas cooler shown in Fig. 51 (left from Fig. 48). The three stages are (1) a cool water stage at 6°C, (2) a gaseous nitrogen stage supplied with nitrogen evaporated in the third stage and (3) a liquid nitrogen stage). The gas leaving the gas cooler is very cold (< 240 K) and has to be heated up again by the exhaust gas heater to ambient temperature before it is recycled to the gas dosing system.

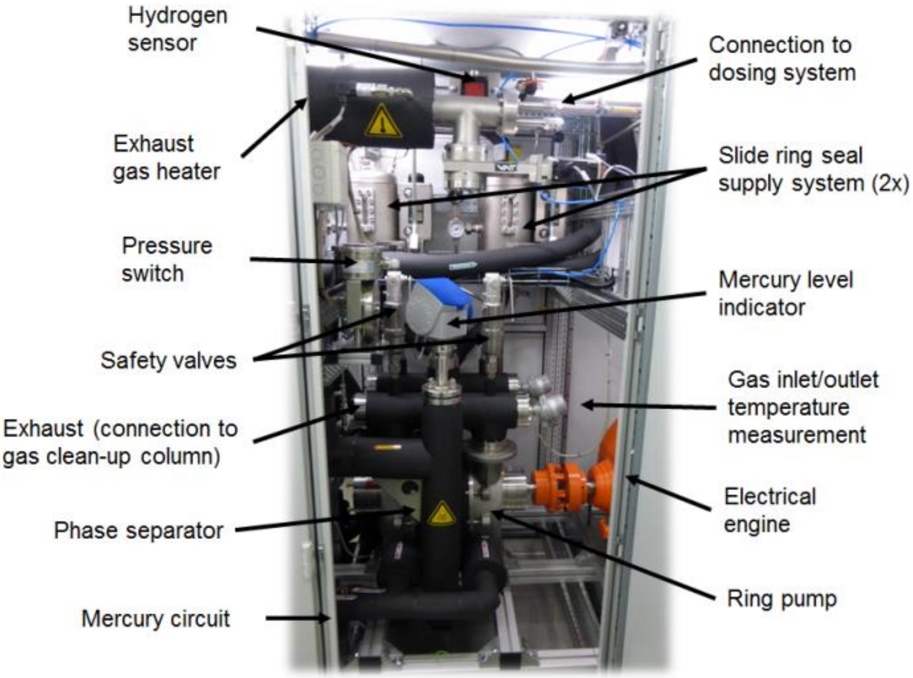


Fig. 50: The mercury ring pump in the housing (1).

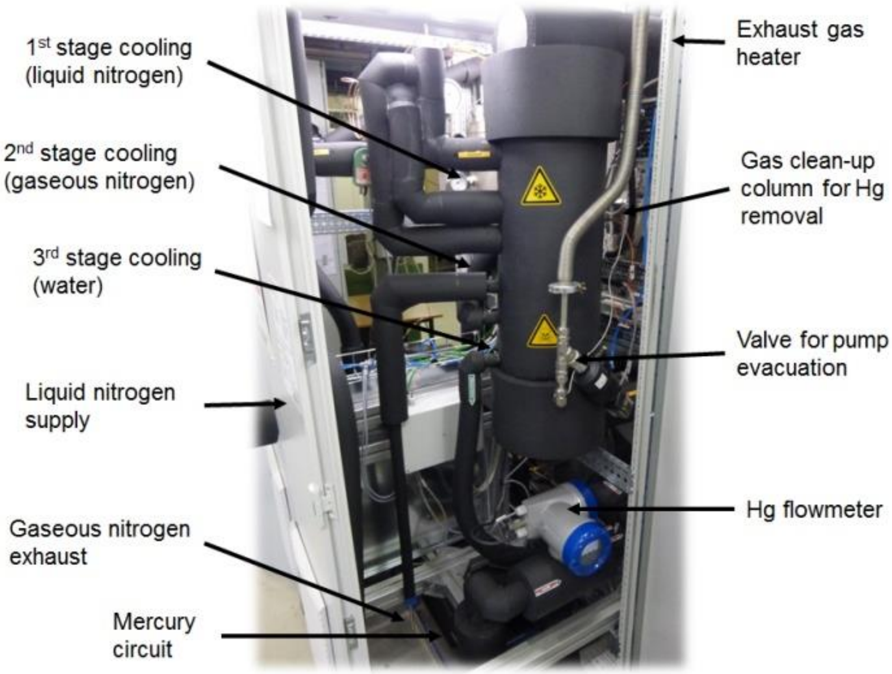


Fig. 51: The mercury ring pump in the housing (2).

The liquid ring pump is equipped with a level indicator that measures the mercury level in the phase separator, a flow meter in the mercury circuit, temperature gauges for the inlet and outlet temperatures and pressure transmitters to register the pressure drop over the gas clean-up column. If the gas cooler is being blocked (e.g. by water coming from the slide ring seal system that is freezing out in the column), two safety valves bypassing the pump open at a pump exhaust pressure of 1 bar(g) and recycle the gas directly to the upstream side.

The first stage of the gas clean-up column is supplied by liquid nitrogen coming from a 200 L Dewar located next to the housing. The liquid nitrogen feed is regulated automatically via an electrical valve that is set to an exhaust gas temperature for the evaporated nitrogen of 173 K. This gaseous nitrogen, after being used for second stage cooling, is exhausted in direction of the water filled bowl. Cool water is used for cooling the 3rd stage of the gas clean-up column, for cooling the mercury circuit (via a fully welded stainless steel heat exchanger) and for cooling the slide ring seal system. Via pneumatic cool water valves, a flow meter and Pt100 thermometers, the waste heat from the pump or alternatively from the full pumping train can be measured.

In preparation of the commissioning of the mercury ring pump in THESEUS, the mercury system has been filled with approx. 238 kg (18 L) of liquid mercury. This was done by opening the flange of the level measurement device and filling the mercury into the phase separator. The mercury inventory accumulates mainly in the circuit (piping, flow meter, heat exchanger) and in the pump itself. The mercury level in the pump reaches to the centre of the shaft, what was the requirement given by the manufacturer.

For a first pump-down experiment, the dosing dome and the pump train is evacuated using the THESEUS service vacuum pump until a pressure of < 1 Pa is reached. Afterwards, the 450 L dosing dome and the pump train is filled with pure nitrogen (quality 6.0) via the gas dosing system until ambient pressure is reached again. Evacuation and filling is done via the vacuum line that connects the roughing pump with the gas cooler; the pump inlet gate valve upstream the ring pump is closed during the whole procedure in order to avoid mercury vapour coming to the dome. Then, the cool water flow and the liquid nitrogen cooling in the exhaust gas cooler is started. After a temperature of 240 K in the gas cooler is reached, the pump inlet valve is opened and the ring pump is started slowly using a variable speed drive. During the following experiment, the data from all metering points have been collected by the Delphin data acquisition system. Within 32 seconds after the start of the ring pump, the electric engine reached its maximum speed of 1500 rpm. This corresponds, due to the transmission of the gear engine, to a rotor speed of 412 rpm. At this speed, the single-stage pump reaches a pumping speed of approx. 100 m^3/h and an ultimate pressure of approx. 6 mbar (compression against atmospheric pressure; pump down curve see Fig. 52). This result is fully according expectation (water ring pumps do only achieve an ultimate pressure of approx. 30 mbar) and therefore successfully demonstrates the pumping principle.

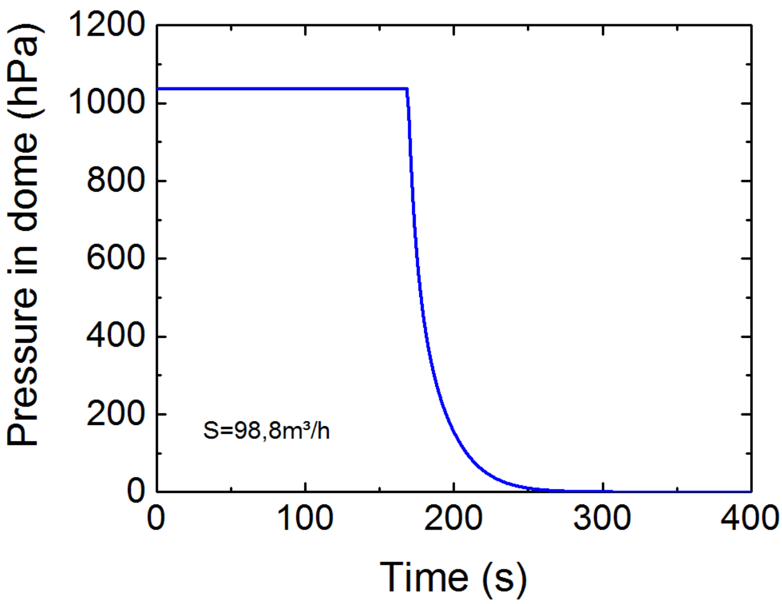


Fig. 52: Pump-down of the dosing dome (0.45 m^3) in THESEUS with the single-stage mercury ring pump.

For simulating two stage liquid ring pumping, the exhaust pressure of the single-stage pump is decreased to 15 mbar using the rotary vane pump installed in the gas dosing system. In this case, the ultimate pressure of the liquid ring pump has been 0.65 mbar. This value is low enough to meet the foreline pressure requirements expected for the DEMO relevant mercury diffusion pumps. Before stopping the ring pump by slowly decreasing the rotor speed, the pump inlet valve is closed again to avoid a potential contamination of the dosing dome when the liquid ring breaks down and upstream- and downstream pressure compensates abruptly through the pump.

As main result of this very first experimental campaign, it could be demonstrated that (i) mercury ring pumps work and (ii) they can reach inlet pressures low enough to use them as fore-pumps for DEMO-relevant diffusion pumps. Furthermore, during all experiments, the pump run smoothly and without vibrations. This is an indication that the effect of cavitation – that is a serious problem for liquid ring pumps when operated close to the vapour pressure of the working fluid – does not play a role in the achieved pressure regime, as it is still two decades away from the vapour pressure of mercury at a pump operation temperature of approx. 30°C.

5.5 Result of the validation process

For all three pumping methods, a gap between the current state-of-the art and DEMO-like pumping was identified. Based on this, experimental facilities have been set-up and experiments have been performed to validate the applicability of the pumping methods under DEMO relevant conditions. For all three methods, this could be done successfully:

For metal foil pumping, superpermeability at relevant pressures (around 1 Pa) using a mild plasma process for generating the energetic hydrogen has been demonstrated. However, the expected performance in view of specific (i.e. metal foil surface related) pumping speed and throughput is still very low and needs improvement. But the results produced in our experiments in a very first step look highly promising.

For diffusion pumping, it could be demonstrated that mercury diffusion-ejector pumping is applicable under fusion relevant throughput and vacuum conditions: Under high vacuum conditions, the pumps work as diffusion pumps with high compression values of several decades. Under burn conditions, with a pressure range of 1 Pa and more, jet (or ejector-) pumping is dominating and allows a high gas throughput at for primary pumps untypically high pressures. In conclusion, the proposed pumping principle (diffusion pumping combined with ejector pumping) will definitely work for DEMO.

For liquid ring pumping, it could be shown that it is possible to use mercury as working fluid, despite of a density 13.5 times higher than the density of the typically used water. Also the achievable ultimate pressure (approx. $3\cdot10^4$ Pa in case of water) is much lower as it is not limited anymore by the vapour pressure of the fluid. In our experiments, it could be shown that a pressure below 100 Pa could be achieved (assuming a two-stage pump), what is sufficiently low to use this pumping method for roughing the diffusion-ejector pumps.

6. Technical realization of the novel vacuum pumping concept

6.1 Identification of vacuum pumps for fusion power plants

6.1.1 Pump performance requirements

For the vacuum pumps in fusion power plants, it is very difficult to estimate the required pumping speeds as this machine is still far in future and gas throughput and pressure ranges cannot be estimated at this stage. What is more advanced is the pre-conceptual design of a demonstration power plant (DEMO), for which gas throughput and pressure can be roughly estimated based on the experience with current machines.

Scaling the gas throughput from ITER (where the numbers are known) to DEMO linear with the fusion power (which would yield a factor 4 for a 2 GW DEMO machine) is considered to be too conservative. This is due to the fact that the total throughput to be taken by the exhaust vacuum pumping system has a number of contributions that scale differently:

1. Burn-up: This denotes the consumption of fuel by the fusion reaction (6 Pa m^3/s DT fuel per GW fusion power, resulting 12 Pa m^3/s for DEMO).
2. Neutral beam fuelling: The required number of Neutral Beam Injector (NBI) heating systems at DEMO and their power is not clear. However, for the ITER configuration (injection of 51 MW with deuterium ions accelerated to 1 MeV) we obtain an injected molecular gas throughput of 0.6 Pa·m^3/s. Even if scaled up to DEMO, this contribution is very small.
3. Core density sustainment: This denotes the loss of particles due to the gradient between the high core density and the low pedestal density. This contribution is 40 Pa m^3/s at ITER [82] and predicted to be ~ 75 Pa m^3/s for a 3 GW DEMO with a major radius of 8 m [83], which scales down to two third for a 2 GW DEMO, namely 50 Pa m^3/s. To keep the core density, pellets have to be injected against the edge transport barrier. This is a process of which we know that it is associated with loss of gas that does not enter the core. It consequently asks for the injection of more gas than mentioned above.
4. Gas fuel throughput via the scrape-off layer: This is calculated to be ~ 205 Pa m^3/s [83].
5. Helium concentration limitation: This denotes an additional fuel throughput to keep the He concentration in the core below 5 %. To have an estimate for DEMO, we scale the number from ITER (40 Pa m^3/s) in the same way as the core through-put scales (50:40), which thus yields 50 Pa m^3/s.
6. Edge Localized Mode (ELM) pacing by pellets: On top there comes additional fuel gas for pellet ELM pacing (if this approach will be implemented). This contribution shall be neglected here.
7. Divertor radiative seeding: Impurities (i.e. heavy gases with a medium or high atomic number) have to be added to reduce the power transported into the Scrape-Off Layer (SOL) and, thus, limit the peak divertor power load. The calculations in [83] showed this impurity seeding rate to be in the order of (integrally) below 0.05 % for Xe and 2 % of Ne, hence negligible. This impurity seeding is established to protect the divertor and ensure wall loads below 5 MW/m^2, which is the currently accepted value under the neutron loads foreseen at DEMO [84] and considerably less than accepted for ITER.
8. Gas puffing to reconstitute confinement for a metal wall environment: This contribution reflects the new findings in AUG or JET with the ITER-like wall, which shows that additional gas has to be puffed to achieve stable plasma. This new result is not yet fully understood and

the results are not all consistent, but an additional gas portion of 50% of the injected pellet throughput is well reasonable thus adding another ~ 160 Pa m³/s. This gas is not fuel, but e.g. nitrogen [85].

Considering all these different contributions, it is obvious that the throughput cannot be fixed accurately at the moment. A rough estimation presented here gives 475 Pa m³/s of gas to be pumped by the divertor pumping system, if no extra gas for pellet ELM pacing is taken into account (this is ideally the case if DEMO fully relies on magnetic perturbation control only). This scaling assumes DEMO to have an ITER-type divertor, which may not be the case. But the main conclusions for the pumping system are independent of the divertor concept. Based on simulations performed for an ITER divertor which had been up-scaled to DEMO size, we expect the pressure ranges to be of similar magnitude [86]. The ultimate base pressure primarily defines the cleanliness in the vacuum chamber and, hence, we expect to have similar requirements in ITER and DEMO. Until we have not learnt anything else from ITER, this also holds for the base pressure between pulses. Tab. 14 gives an overview of the pumping parameters estimated for a DEMO machine.

Tab. 14: Assumed DEMO pumping parameters. [87]

Parameter	Value
Base pressure for hydrogen isotopes	$<10^{-5}$ Pa
Typical divertor pressure during plasma operations	1-10 Pa
Maximum average throughput during plasma operations	400-600 (Pa m^3)/s
Base pressure between pulses	$< 5x10^{-4}$ Pa
Primary pumping speed	Several 100 m^3/s
Roughing pumping speed (pump-down in 24 h)	Several 1000 m^3/h
Dwell pump-time	Approx. 20 min

Throughput and divertor pressure directly relates to the total required pumping speed. It is absolutely clear that the total pumping speed has to be distributed among a certain number of (identical) pumps, as it is much too large for one single pump. Hence, the review done in the following section assumes that not all gas has to be pumped by only one pump but by a reasonable number of pumps with accordingly smaller pumping speeds. For the primary pumps, the pumping speed is of the order of 10 m³/s; for the roughing pumps, it may amount to 100 m³/h or higher.

It has to be kept in mind that due to the installation of the pump, a significant conductance loss is expected what has to be compensated by larger pumps. So a simple estimation of the pumping speed by throughput over divertor pressure, divided by the number of pumps, may be much too optimistic.

6.1.2 Overview of pumps available on the market

Metal foil pumps

Up to now, metal foil pumps are not available on the market.

Diffusion pumps

On the market, there is a large variety of diffusion pumps available, but only in a circular-shaped design and with oil as working fluid. Some of the pumps do use a jet stage that allows an operation towards higher foreline pressures. Large manufacturers are EDWARDS (UK), Varian (US), HSR (Lichtenstein) and a number of smaller companies in India, where this kind of pumps is still very popular.

In currently available pumps, the sump that is always heated electrically and the nozzle system for guiding the oil vapour through the pumps is typically made out of alumina as this material can be deep-drawn easily during the manufacturing process. In some cases, pumps with a stainless-steel casing, or even a stainless-steel nozzle system, are available. Normally, especially for large pumps, no baffles are installed as part of the pump. If necessary, external baffles (water- or liquid nitrogen cooled) must be used and installed upstream the pump. Downstream the pumps, no baffles are available at all.

All pumps on the market apply a design that is not applicable in fusion for the following reasons: Firstly, if a circular shaped pump would be used, this would immediately lead to a large overall working fluid inventory of up to several tons per pump. For safety and economic reasons, this must be avoided. The reason therefore lies in the circular pump design: The diameter scales with pumping speed and the inventory increases quadratic with the diameter.

Secondly, mercury as working fluid solves nickel and chromium relatively well [88]. This is especially a problem when using stainless steel at elevated temperatures above 200°C [89]. Major problem is not the dissolving of the stainless steel (therefore the corrosion rates are much too low) but the increase of the boiling temperature of the mercury. How strong this effect is not probably known [89]. Moreover, mercury forms amalgams. These substances are weak materials what leads to a decrease of mechanical stability and leak-tightness of the affected components. Some commonly used materials – even for tritium containing systems – may not be used any more: Aluminium, copper, silver and gold are excluded from their application. This seems to be easy to realize but a closer look to a lot of all-metal and full stainless steel components (like valves and seals) shows that they are almost always covered with a thin layer of alumina, silver or gold to avoid cold shuts and to increase the lifetime and the leak-tightness.

Thirdly, mercury diffusion pumping can only be used without baffle down to an inlet pressure of approx. 0.1 Pa (if cooled with water at a temperature of 20°C), because the vapour pressure of mercury at the given pump temperature is relatively high and limits the ultimate pressure to this value. Therefore, and to avoid a contamination of the torus upstream the pump, inlet baffles are absolutely necessary. But if an internal or external baffle on the pump inlet is applied and operated at a very low (e.g. liquid nitrogen) temperature, it would freeze out the mercury and block the inlet after a certain operation time. On the outlet side of the pump, the problem is very similar. This a huge disadvantage, as the pump should work continuously.

<u>Liquid ring pumps</u>

Liquid ring vacuum pumps are very commonly used pumps in the chemical industry. The pumps are used typically in rough vacuum applications, where moderate vaccua at high pumping speeds are needed. Typical examples are dryers in the paper industry. Here, machines with diameters of more than two meters and a driving power of more than 0.5 MW are available. On the market, a lot of manufacturers are active, building pumps in all sizes, designs and using different materials incl. ceramics or polymers for wheel and casing. In Europe, especially in Germany, Sterling SIHI (Itzehoe), CUTES (Friedrichsdorf), Speck Pumpen (Roth) or Hermetic (Gundelfingen) are some of the large manufacturers.

Liquid ring pumps are typically one- or two-stage pumps using water or other fluids (like oil or other organic substances) as working fluid. The number of stages depends on the pressure that shall be achieved in the system: typically more than one stage makes no sense as the ultimate pressure is anyway limited by the vapour pressure of the fluid and the focus of the pumps is on a high pumping speed. In consequence, two-stage pumps are very rare on the market and also other working fluids with much higher densities than the ones mentioned before are not used and operational experiences or performance data do not exist.

The wheel in a liquid ring pump is typically levitated by normal fat lubricated bearings located outside of the casing and sealed against the suction chamber by slide ring- or labyrinth seals. However, there are also hermetically tight pumps on the market using e.g. double slide ring seals , magnetic coupling or gap pole engines with hydrodynamic or ceramic bearings running in the working fluid.

Liquid ring pumps are available as single- and double acting pump, depending mainly on machine size. In case of double acting pumps the gas enters the liquid ring from both sides of the suction chamber whereas in single acting pumps, the gas enters only from one side. Double acting pumps allow for larger pumping speeds.

It must also be noted that liquid ring pumps are the only pumps on the market that can be used for the compression of explosive gases (ATEX Zone 0), if special requirements on pump instrumentation are fulfilled. Reason for this is the working principle itself: The pump does not get hot and contacts between moving components (i.e. the wheel) and the casing are avoided due to large gap widths. However, even if sparks would be generated (e.g. in the bearing), they would be immediately extinguished by the working fluid.

6.1.3 Design proposal of vacuum pumps for fusion applications

Diffusion pumps

For diffusion pumping, large-scale diffusion-ejector pumps with a pumping speed of some 10 m³/s and with mercury as working fluid must be used. Furthermore, a design is necessary that does not show the limitations of currently available pumps.

A solution to reach very low working fluid inventories in the pumps is the use of an external boiler for the mercury instead of a sump, a feature that has already been tested in the past [90] in linear-shaped mercury diffusion pumps. Here, the boiler is located right below the pump and works like a heat exchanger: Liquid mercury coming from the pump flows into it (due to gravity forces) and is evaporated again. The vapour leaves the boiler and supplies the pump nozzles. The size of this external device does not scale much with the pump size, like it would be the case for the sump of a circular-design pump, only with boiler inventory.

The pump should be made out of stainless steel with low magnetic permeability in order to avoid a distribution of the magnet system of the machine. To avoid material incompatibility issues between mercury and the steel, especially at hot components like the boiler or the nozzles, enamelled of these components must be done. By covering the metal surfaces with a thin layer (µm-scale) of glass, a direct contact between mercury and the steel can be avoided. Glasses like SiO_2 are perfectly mercury and tritium resistant. Enamelling can be done with components in almost arbitrary size, with complex geometries (if there are no sharp edges) and also with non-metallic components like alumina and copper that would form amalgams. There are a number of companies on the market that are specialized to these procedures. The upper limit of the application temperature is approx.

250°C what is fully sufficient for diffusion pumps. Experiences from companies working with mercury can report good experiences with the use of enamelled components [89].

A solution to avoid pump stops for baffle regeneration is the integration a two stage baffle upstream the diffusion pump. The first stage (in direction of the gas flow) should be at sufficiently low temperature and optically tight (chevron-type) in order to ensure that every vapour molecule hits the baffle plates and is removed by freezing out. This guarantees that practically no mercury vapour can flow back to the MFP in direction of the torus. At a first-stage baffle temperature of 200 K, the mercury vapour pressure is ~10^{-6} Pa, which is about two decades lower than the partial pressure that is allowed in ambient air ($2 \cdot 10^{-4}$ Pa) [91]. If it is found in a safety study that these two decades are not enough, the temperature can be reduced correspondingly. The phase diagram of mercury is shown in Fig. 53 [92]. The second baffle is located between the first stage baffle and the diffusion stages. The temperature here must be slightly above the triple point of mercury (234.3 K), e.g. at 240 K. This baffle removes the major part of mercury vapour by condensing it. For keeping the pump compact and the complexity (like the number of components and seals) of the diffusion pumping system low, the two baffle stages should be integrated in the pump and optimized in view of conductance loss, heat load and the effectivity to avoid mercury vapour backflow.

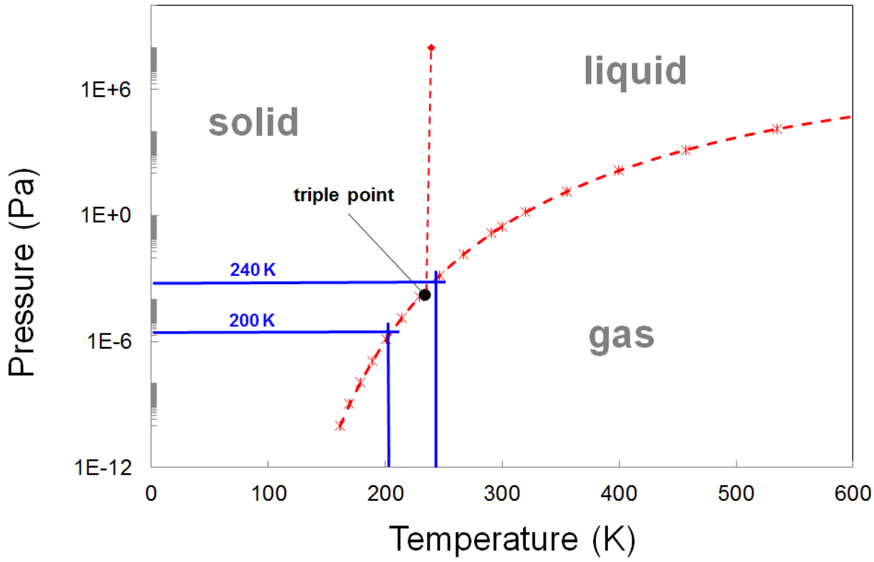


Fig. 53: Phase diagram of mercury.

In conclusion, the diffusion pump required to realize the pumping system identified before must be a diffusion-ejector pump in a linear-shaped design. Mercury must be used as working fluid and all stainless steel in contact with hot liquid mercury must be protected by enamelling. The pump must be equipped with an integrated two-stage baffle, operating at 200 K and 240 K, respectively. Also an integrated outlet baffle must be foreseen to avoid that mercury might leave the pump towards the roughing system (though this would not be a serious problem as the roughing pump will apply mercury as well).

Liquid ring pumps

On a first glance, it seems to be not a problem to find a manufacturer that can supply a hermetically tight pump in the required (some 100 m³/h) size and with materials resistant against mercury (i.e. without internal polymers). Also the problem of a not existing two stage pump can be easily solved: Two pumps in series with two separate working fluid cycles and two phase separators will fulfil the same task.

The major problem is the tritium compatibility. Due to the stringent leak-tightness requirements, the pump has to be hermetically tight what asks for either a magnetic coupling or the use of a gap pole engine. The latter option is not a good solution as here, the mercury as well as the tritium will get in contact with the by polymers insulated electric winding. Magnetic coupling using standard electric drives would thus be favourable. However, this solution needs levitation for the internal wheel what is typically done by hydrodynamic bearings. These bearings work perfectly well if e.g. water is used as working fluid: in this case, due to the rotation of the shaft, water is pushed below it, lifts it and allows levitation without contact between shaft and liner. Unfortunately, this system will not work for mercury as working fluid, as due to the high surface tension of mercury, the shaft will not be wetted, the lifting does not work and the shaft rotates in contact with the liner, leading to a quick failure. A way out of this dilemma would be the use of ceramic ball bearings that are designed to run dry or with any surrounding fluid.

Liquid ring pumps exhaust usually both, the working fluid and the pumped gas to remove the compression heat. Due to the high density of mercury, this capability will be very limited. A pre-separation in the pump casing should be foreseen to guarantee a closed mercury circuit via a heat exchanger. In case the flow in this circuit is not sufficient for removing compression and waste heat produced by the pump, a cooling jacket should be foreseen for pump housing and magnetic coupling.

In conclusion, for fulfilling the pump task defined above, large double acting mercury ring pumps are required. To make them hermetically tight, a magnetic coupling must be foreseen with internal ceramic ball bearings. For cooling, cooling jackets must be foreseen around the pump and magnetic coupling. To maintain a working fluid flow via the heat exchanger, a mercury fore-separation is needed.

<u>Metal foil pumps</u>

The metal foil pump has to be installed close to the torus. At this location, there is strong neutronic radiation. This means, the pump can only be handled remotely in case of failures or maintenance. A modular pump design is thus favourable that can be installed and removed in the pumping duct using remote handling tools.

A pump in a tubular design is considered as technically most promising, considering especially manufacturability and stability. The pump would work similar to an osmoses module: Gas would enter the pump from one side of the ‘pipe’, consisting out of the metal foil, and flows through it. In the very first part of the pump, mainly protium will penetrate the foil. If necessary, this gas can be removed from the pump separately or together with the retentate and treated in the tritium plant, as protium is not used as fuel and must be removed from the circuit. In the central and last part of the pump, mainly deuterium and tritium is being pumped by the foil. All other gases (retentate) will leave the pump unaffected towards the tritium plant.

The metal foil must be kept at an elevated temperature during operation (to avoid embrittlement due to phase changes in the metal lattice), what can be done by an electrical current that flows directly through the foil. Also the plasma has to be generated inside the pump. A plasma based method shall be used, what asks for the implementation of a plasma generator inside the pump.

6.2 Detailed description of proposed vacuum pumps

6.2.1 The metal foil pump

For metal foil pumps, it is very difficult to provide a more detailed description of the pump design. Before a design can be made, a clear understanding has to be developed how the plasma or the atomic hydrogen is being generated and what infrastructure is required for pump operation (e.g. foil heating, pump cooling, instrumentation etc.). Also the metal foil performance plays a major role (as this defines the foil surface required per pump and thus the pump size), as well as requirements on remote maintenance, operation and control. To define all these requirements require is definitely future work (see also chapter 7) and can only be done as soon as the fusion reactor design evolves.

6.2.2 The diffusion pump

Considering the design characteristics outlined in the chapter before, a diffusion pump in a novel design has been developed. A sketch of this so-called Linear Diffusion Pump (LDP) is shown in Fig. 54: In the upper part of the pump, a two-stage baffle has been integrated. The first stage is optically tight whereas the second stage is an arrangement of parallel plates. Once the gas has passed the two baffle stages, it is being pumped by three linear diffusion stages. The mercury vapour, as well as the heat transfer fluid for baffle cooling, is supplied from the side (not shown in Fig. 54). The mercury, that is condensed out by the cold plates, drops to the pump bottom and leaves it via a small pipe towards an external boiler. In the lower part of the pump, the compressed gas turns and flows upwards towards the two parallel ejector stages (Fig. 55), located in the upper part of the pump. After being pumped compressed there, the mercury vapour is condensed out in a water cooled, double walled pipe and then guided over the side part of the second stage baffle where again mercury is condensed out.

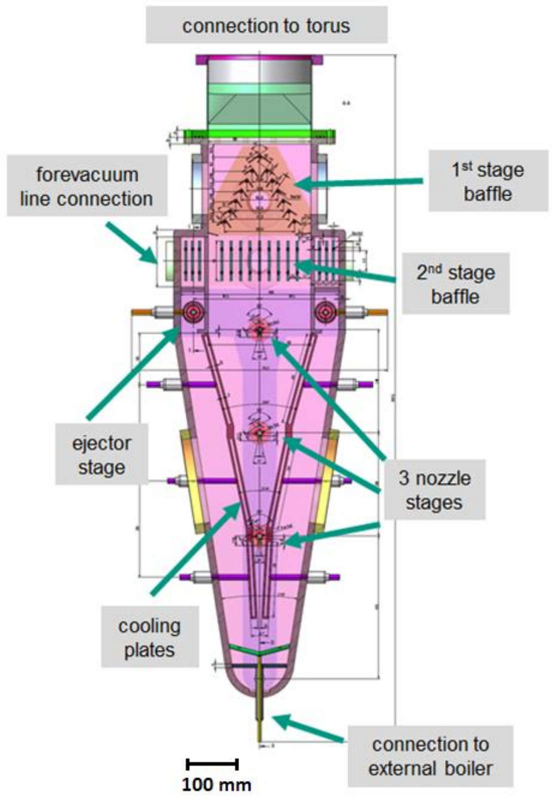


Fig. 54: Pre-conceptual design of a linear diffusion pump.

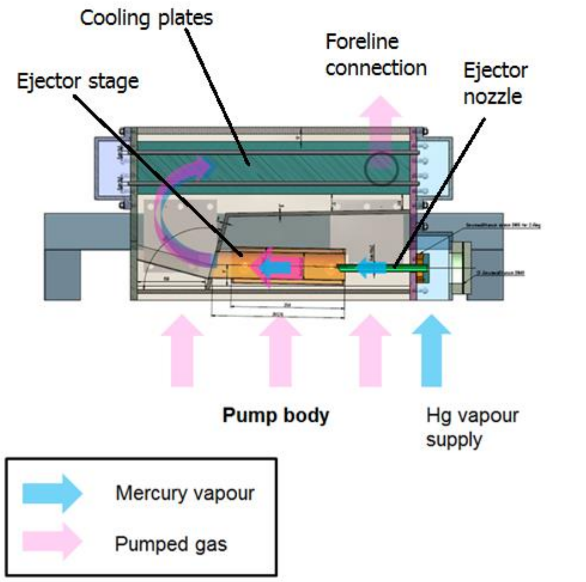


Fig. 55: Pre-conceptual design of the ejector stage (side view).

For commissioning and decommissioning (mercury removal), the pump must be fully bakeable using non-electric methods (heating wires would not survive the neutronic radiation and the magnetic fields close to the reactor). This can be realized supplying the baffle systems with hot, instead of a cold heat transfer fluid. Also the cooling plates can be supplied with hot (pressurised) water. For bake out, at least 150°C are necessary to remove all water and mercury residual [89]. This bake-out scheme has to be considered in the design phase to make sure that all baffle- and cooling plates can withstand the corresponding pressure.

For tritium compatibility reasons, a pump design using only all metal seals must be developed. This asks for strong flanges as the forces needed for metal seals are much higher than for polymer seals. All seals have to be covered with a pure iron coating: The pure iron is perfectly mercury compatible and relatively soft, what guarantees a good sealing performance. To avoid magnetic distributions of the magnetic fields needed for plasma containment and to achieve a low tritium permeation rate through the pump walls and a long pump lifetime, the pump body must be made out of stainless steel.

The external mercury boiler (not shown in Fig. 54), is not part of the pump design. It is considered as tube heat exchanger with minimal mercury volume, where the mercury, returning from the pump, is evaporated using a heat transfer fluid. Ideally, this can be the machine coolant as it is on a sufficiently high temperature level. If this is realized, this pumping solution would be very efficient as only minimal external power or electrical power is required for pump operation.

This pump design is based on an improvement of the linear mercury diffusion pump, investigated in Livermore Research Laboratory in 1953 [90]. Assuming that the performance of such a pump will not be improved very much by the current design, a pumping speed of approx. 10 m^3/s and meter pump length can be expected.

6.2.3 The liquid ring pump

A liquid ring pump that includes the design characteristics mentioned in chapter 6.1.3 has been developed in cooperation with an industrial partner (Hermetic GmbH, Gundelfingen, Germany). A sketch of this design is shown in Fig. 56. As starting point, the design of the pump used during the proof-of-principle testing in THESEUS (LVPM 600 by Hermetic, see chapter 5.4.3) has been used. This pump is to a large extend already relevant as it is a mercury-adapted double acting pump with a pumping speed already in the order of what is required for DEMO. However, the following major modifications had still to be implemented:

- Replacement of all polymer seals by metal seals with pure iron coating (Armco by Helicoflex).
- Modification of the flanges to be suitable for the use of all-metal seals (A, F).
- No use of polymers on the internal control disc. This means that the maximum pumping speed is reduced in benefit of a low ultimate pressure.
- Implementation of ceramic bearings (CEROBAR, silicon nitride bearings with stainless steel cage; C, E) and magnetic coupling to make it hermetically tight (target leak rate: < 10^{-9} mbar l/s).
- Installation of cooling jackets (B, D) for pump housing and magnetic coupling with ¾” cool water connections (G).
- Implementation of a drain connection (H) for pump filling and draining and a fore-separation connection (F) for mercury.

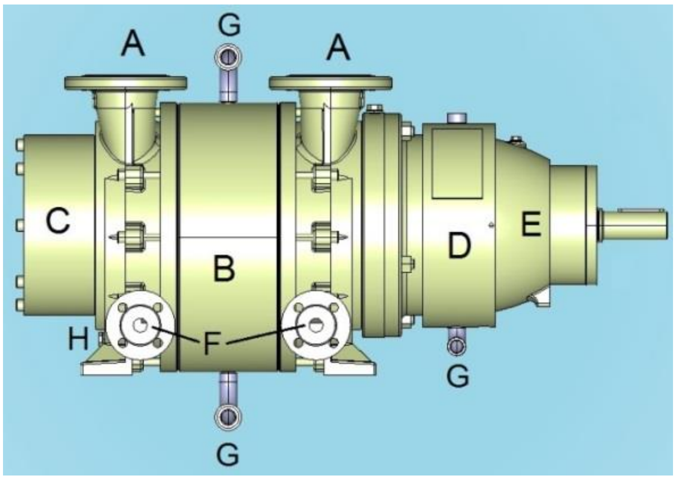


Fig. 56: Design of the fully tritium compatible mercury ring pump.

The pumping speed of the pump before modifications was 600 m³/h (working fluid: water). For mercury operation, the mechanical forces to the pump (especially to the housing) are much higher due to the higher density of the working fluid. To avoid a complete new pump development, it has been decided to reduce the rotor speed of the pump to a value where the same mechanical stress acts on the pump as if operated with water. The calculation can be done as follows:

For different working fluids, the kinetic energy of the liquid ring E_L is given by

$$E_L = V_L \cdot \rho \cdot v_L^2 \,, \qquad (6.1)$$

where V_L is the rotating liquid ring volume, ρ is the density of the working fluid and v_L the speed of the liquid ring. The dependency of the liquid ring speed at constant ring energy from the density of the working fluid (indicated by ') is given by

$$v' = \frac{v}{\sqrt{\frac{\rho'}{\rho}}} \,. \qquad (6.2)$$

For mercury, ρ'(mercury)/ρ(water) = 13.5. This means that the engine speed must be reduced by a factor of 3.7 to keep the kinetic energy in the liquid ring constant. The four pole electric engine (normally running at 1'500 rpm) has to run now at 390 rpm, what can easily be realized by a gear motor with a transmission ratio of approx. 3.5 and combined with a frequency transformer.

As liquid ring pumps are volumetric pumps, the rotor speed is related directly to the pumping speed: If it is reduced by a factor of 3.7, the pumping speed will be reduced to 160 m³/h, assuming ideal conditions and linear scaling.

6.3 The KALPUREX process

6.3.1 Pump arrangement and gas processing

The Direct Internal Recycling (DIR) concept foresees a separation of pure unburnt fuel from the exhaust gas close to the machine by a metal foil pumps and its recycling without being treated in the tritium plant. The KALPUREX process (acronym for 'Karlsruhe liquid metal based pumping process for fusion reactor exhaust gases') is the technical realization of this DIR concept with all required pumps and infrastructure [93]. In the KALPUREX process, all three pumps described before are used for pumping the reactor exhaust gases continuously.

As the gas separation of unburnt fuel (deuterium and tritium) shall take place as close as possible to the torus in order to minimize piping and conductance losses, the metal foil pump must be used as first pump, installed very close to the divertor. A schematic view of this concept is shown in Fig. 57. To ensure the vacuum conditions for metal foil pump operation, two pump trains have to be used for further exhaust gas processing: One for pumping the permeate (the pure fuel that is separated and pumped by the metal foils) and one for the retentate (the residual gas that is not being pumped and enriched with impurities).

The permeate is compressed by the diffusion pump and the liquid ring pump to a pressure that is required for the fuelling system and recycled directly to the fuelling and storage systems (→ DIR). The retentate is compressed by a second identical pumping train to the pressure required in the tritium plant, where the gas is cleaned up and further processed before it is also fed to the fuelling systems. If the performance of the Metal Foil Pump (MFP) and/or the fuelling systems allow for it (to be confirmed in future R&D programmes), the first pumping train (for the permeate) may even be omitted, what would lead to a further simplification of the whole pumping system.

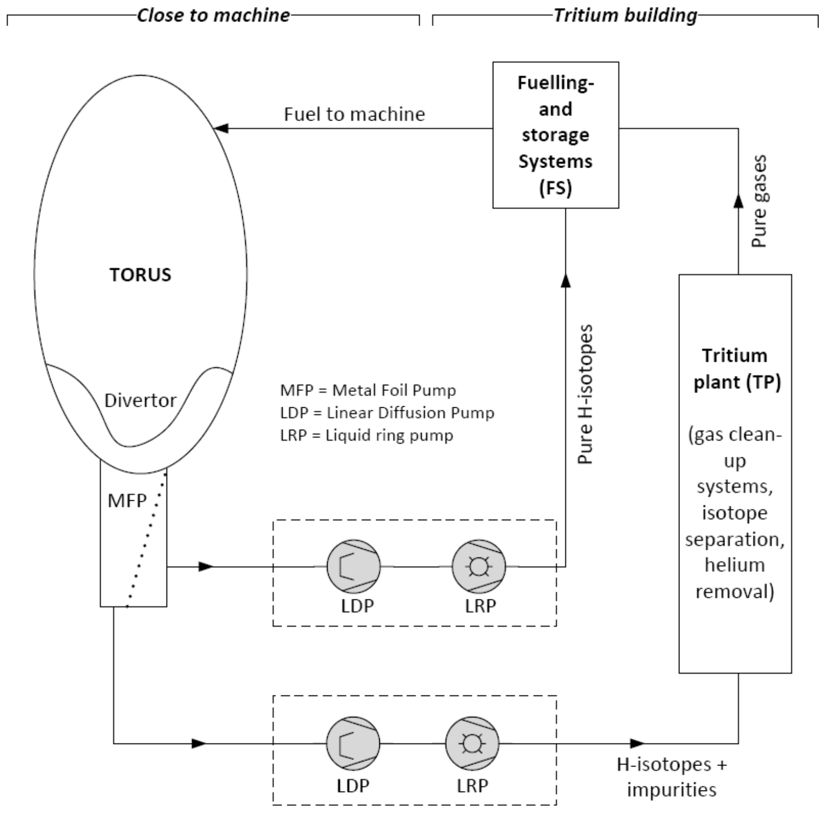


Fig. 57: Schematic view of the KALPUREX-process.

6.3.2 Infrastructure requirements

Metal foil pumps require an ‘atomizing’ device that converts the neutral hydrogen gas molecules upstream the pump into energetic hydrogen. As discussed before, this can be done using RF plasma. A RF plasma source requires a supply by electromagnetic waves that may be transferred to the pump by waveguides from a magnetron installed abroad. Except of this, only a small infrastructure is required: The pump itself has to be cooled actively (by cooling water or cold gas) and the metal foil has to be heated by an electric heating system.

The working principle of diffusion pumps is based on the evaporation of a working fluid cycling inside the pump. Hence, diffusion pumps need a heating system and a cooling system at the same time. Including the heating system for the mercury boiler, four supply systems are required for pump operation: The boiler heating system, a cooling system for wall cooling and the two baffle cooling systems. The wall cooling system can be realized by a standard cool water system whereas a cooled compressed gas as heat transfer fluid is suggested for the two low temperature systems (see section below). For boiler heating, the same gas system can be used, but at a higher temperature level (~ 470 K). This heat transfer system was also selected due to safety reasons (no water can enter the pumps in case of an internal leak in the baffles or boilers) and a high level of radiation resistance (e.g. oil or water/glycol as heat transfer fluids would decompose under radiation). An overview of the infrastructure requirements for diffusion pumps is given in Fig. 58.

In the liquid ring pumps, the working fluid absorbs the compression heat and is exhausted together with the pumped gas. The liquid mercury is then separated by a phase separator on the exhaust of the ring pump and recycled back to the pump by using a heat exchanger where the compression heat is removed via a cooling water flow.

The exhaust gas of the LRP is loaded with mercury vapour that has to be removed before the gas enters the tritium plant or the fuelling systems. Therefore, an exhaust gas cooler has to be installed that cools the gas down to a temperature of 200 K. To avoid a freezing and thus a blocking of this cooler, the gas has to be cooled stepwise with a 240 K intermediate stage, following the same concept as already employed for the LDP. These temperature levels have been selected as they are anyway available for the diffusion pump. An overview of the infrastructure requirements is given in Fig. 59.

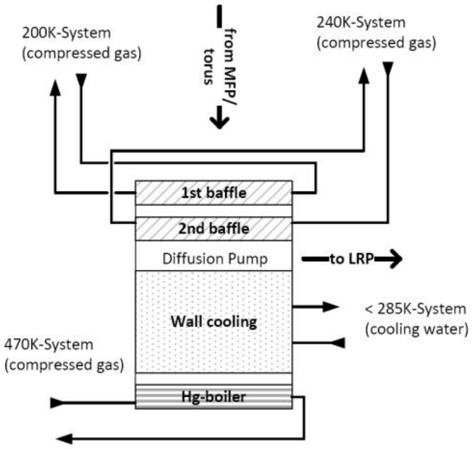


Fig. 58: Infrastructure required for the diffusion pump.

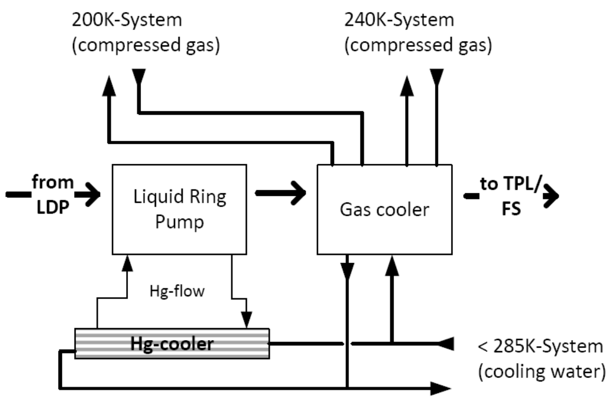


Fig. 59: Infrastructure required for the liquid ring pump.

In total, one cooling water systems and one compressed gas system (at three different temperature levels, i.e. three circuits) is needed. This leads to a set of eight ring lines (four circuits, each with feed- and return line) for pump supply and two forevacuum lines (that connect the diffusion pumps with the liquid ring pumps). The connection of the supply systems should be done from two opposed sides of the ring as this allows a reduction of the required ring line pipe diameters.

To provide the infrastructure required for operating the different pumps, a support facility is needed, the pump support plant (PSP). The facility is connected to the primary pumping systems (metal foil pumps and diffusion pumps) via the pipe network described before. The cooling water system of the PSP is rather conventional. The situation for the gas circuits is different: To transfer the required heat loads at a relatively low mass flow (which would imply a low required pumping power and small pipe diameters), a high heat capacity and thus a density is needed which immediately corresponds to a high gas pressure. Furthermore, the gas should not be flammable and it should not activate or decompose under radiation. Nitrogen or noble gases may be suitable as heat transfer gases.

The compressed gas is circulated via hot- and coldboxes, where it is heated or cooled to the required temperatures. Inside the boxes hot or cold ejector pumps are located to circulate the gas at a pressure of some MPa and to compensate the pressure drop caused by the pipes and heat exchangers. The ejector pumps need for operation high pressure gas that is provided by a compressor that compresses a partial flow of the circuit to the required pressure. In order not to feed the compressor with gas at a too high or –cold temperature, economizers for this partial flow have to be foreseen in the boxes.

The heat required for mercury evaporation in the diffusion pumps can be extracted from the machine coolant, what makes this pumping system very efficient. Only for start-up, an electric auxiliary heating system is necessary. As simplification for DEMO, the same electrical heating- and pressurized gas system could be used also for baking the machine. This is a huge advantage, as only one system is needed for vacuum pumping and machine baking. This reduces complexity, the required space and costs. The cooling power for the 200 K and 240 K circuits can be provided by e.g. the evaporation of liquid nitrogen or the connection to a refrigerator.

6.3.3 Space required for primary pumping

In this section, the number of pumps and the required space (i.e. the number and size of pumping ports) shall be estimated on basis of the latest DEMO design [94]. Therefore, the pumping speed that has to be provided to the plasma must be known. This is a complicated exercise as it depends on divertor pressure, fuel throughput and on the duct conductance that depends on the flow regime. However, to have an estimation of the number of required pumping ports, the pressure- and throughput estimation done in chapter 6.1.1 can be used.

As always in vacuum technology, the conductance plays a very important role. It is thus necessary to estimate this influence based on the pumping port geometry. To make an estimation, the following simplifications have to be done:

- The distance from the diffusion pump inlet to the divertor can be estimated as a circular pipe with a length of 10 m and a diameter of 2 m. This gives a L/D-value for this hypothetical pipe of 5.
- The optical tight baffle in the diffusion pump (required to avoid any mercury flowing back to the machine) has a transmission probability of 0.3. This value is based on experiences in designing vacuum baffles and is considered to be realistic.
- The pumped gas is pure hydrogen.
- All formularies and estimations used here are only valid in the free molecular flow regime. More detailed calculations would require an enormous simulation effort and an exact knowledge of all geometries and performance parameters. However, this assumption leads to a worst-case estimation.

For the following calculations, these numbers will be used:

- The maximum fuelling rate of 600 Pa m^3/s is assumed, the pressure during burn is 12 Pa. This is based on the values given in Tab. 14 in chapter 6.1.1. (The choice of this pressure will become obvious in the discussion below.)
- The diffusion pump will provide a pumping speed (if the internal baffles are neglected) of 10 m^3 per second and metre pump length. This number has been chosen as this is considered to be a realistic value for mercury diffusion pumps in a linear design [90]. Maybe optimizations in future will lead to higher values.
- On each pumping port, two pumps can be installed next to each other with a total length of 4 metres (2 x 2 m).
- A temperature of 300 K is assumed for the gas.

Based on this, the required overall pumping speed S_{eff} is given by

$$1/S_{eff} = p/Q - 1/C_{tot}, \qquad (6.3)$$

where p is the divertor pressure, Q the fuelling rate and C the conductance of the pumping duct reduced by the baffle inside the diffusion pump. In a first step, the overall Conductance C_{tot} must be calculated. This can be done by

$$C_{tot} = w_{duct} \cdot w_{baffle} \cdot A_{duct} \cdot v_0. \qquad (6.4)$$

w_{duct} describes the transmission probability of the molecules through the pumping duct and w_{baffle} the transmission probability through the baffle inside the diffusion pump. A_{duct} is the area of the pumping duct and v_0 the mean velocity. This is given by

$$v_0 = \sqrt{\frac{k_B x T}{2 * \pi * m_0}}. \qquad (6.5)$$

Here, k_b is Boltzmann's constant, T the temperature and m_0 the mass of one molecule. What is still missing is the transmission probability for the molecules through the pumping duct (w_{duct}). This value can be estimated according [58] by

$$w_{\mathrm{duct}} = \frac{1}{1 + {}^{3}/_{4} * {}^{\mathrm{L}}/_{\mathrm{D}} * \mathrm{x}}, \qquad (6.6)$$

Where x can be taken from [58] dependent on the L/D ratio. Based on all these assumption, a required overall pumping speed S_{eff} of approx. 620 m^3/s can be calculated.

Assuming this number, all 16 ports have to be equipped with pumps (16 ports x 4 m pump length per port x 10 m^3 pumping speed per meter pump). If the calculations are now repeated for a higher divertor pressure, one will immediately find that the number of required pumps drops dramatically with raising pressure. E.g. if 15 Pa can be tolerated (i.e. an increase of only 3 Pa), the number of required pumping ports drops from 16 to only 4. On the other hand, if a value of less than 12 Pa (e.g. 10 Pa) is used for the calculation, a negative value for the overall required pumping speed results. This is physically not feasible and means that (with the assumptions done here) no lower pressure values of 12 Pa can be reached in the divertor region at a fuelling rate of 600 Pam^3/s, independently of the number and performance of the installed pumps. A divertor pressure of 12 Pa is thus a worst case scenario that asks for an equipment of all 16 pumping ports with vacuum pumps.

This calculation shows that the influence of fuelling rate, pressure and conductance is very strong to the design of the vacuum system. To come up with a proper system design, all parameters have to be properly defined and also a strong focus has given to the conductance- and divertor modelling work in future. It must also be noted that the calculation done above does not consider the pump down to the required base pressure in a given dwell time. This calculation depends in addition on much more parameters (e.g. materials, temperatures, outgassing values, impurities etc.) for which no reasonable assumptions can be done at this early design stage.

6.3.4 Integration of the primary pumps

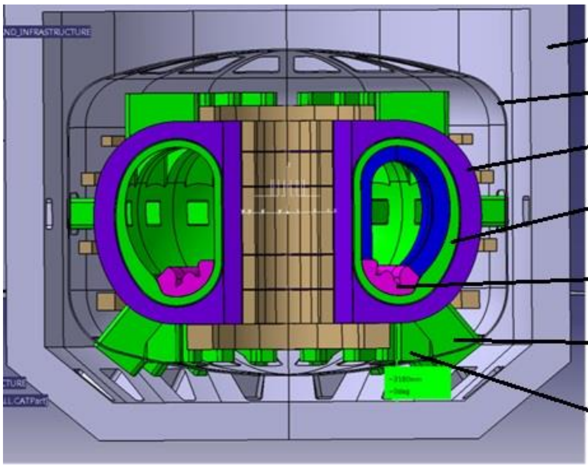
The pump location is important to known already in an early design stage as it has a strong impact on the overall machine design. The location is being defined by

- the pump itself (as not all pump types can be installed in any position),
- by other machine systems (that limit the space available for pump installation, e.g. due to the magnet system),
- the required pumping performance (that defines the size of the pumps) and
- the pump infrastructure requirements (e.g. piping and remote handling needs).

The current DEMO design foresees a divertor configuration [94]. This means the pumps must be connected to the below-divertor region to pump out the gas and the impurities that accumulate there. The gas and impurity accumulation there is based on physical transport processes and must be considered as boundary condition for the pumping system [82, 83]. The pumps must thus be located below the machine; upper and side positions are not an option. In addition, long pumping ducts must be avoided as long distances between torus and pump would lead to a low conductance. If long pumping ducts cannot be avoided, this would require a large number of pumps and ducts connected to several positions to the sub-divertor region to meet the pumping requirements. This increases the complexity of the overall system and must be avoided.

A block diagram of the pump arrangement on this position has already been presented in Fig. 55 with a metal foil pump as first pump, followed immediately by two linear diffusion pumps for pumping the pure fuel and the residual gas flow. In this chapter, it shall be discussed how and where the pumps can be installed on a DEMO machine. As basis for this discussion, the latest DEMO design [94] shall be used. Even if this design is still changing, the overall configuration will stay the same. Furthermore, the considerations done here consider that the conductance of the pumping system is limited by the pumps and ducts and not by the divertor in the torus.

A half-model of the tokamak with torus, magnets, cryostat and surrounding concrete bio-shield is shown in Fig. 60. Fig. 61 shows a cut-view through the torus of a Tokamak. Here, one segment of the vacuum vessel (blue) is shown with a vertical pumping port and the angled divertor maintenance port.



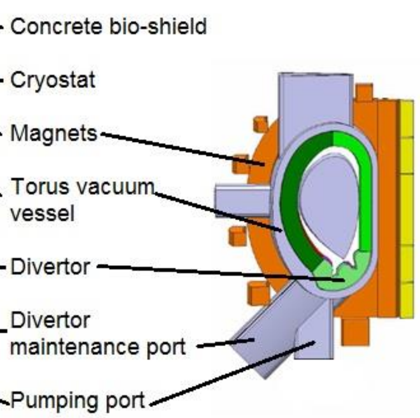


Fig. 60: Cut-view through the Tokamak with surrounding cryostat (vacuum vessel) and concrete bio-shield. [91]

Fig. 61: Cut-view through one Tokamak segment with a pumping port attached to the divertor maintenance port.

Independent of the number of required pumping ports, the metal foil pumps and the diffusion pumps have to be installed as close as possible to the machine. Considering that especially the MFPs must be accessible in case of maintenance or failures, it would be ideal to install the pumps outside the pumping duct or even outside the bio-shield. Outside the bio-shield would mean that a longer pumping duct with a correspondingly higher conductance loss is required. Furthermore, a dedicated room with extra bio-shield would be needed below the torus. On the other hand, an installation in a 'pumping room' would provide more space and would allow an expansion of the port, leading to maximum utilisation of the port cross-section as illustrated in Fig. 62. This is a huge advantage over the installation inside the port.

In this configuration, the MFPs could be installed horizontally with an upstream inlet valve. The gas being pumped by the MFP (pure fuel) is guided by the port to one diffusion pump, the residual gas flow passes the tubular pump unaffected and reaches finally the second LDP. A set of valves on the inlet of the port extension can be opened during dwell pumping. In this case, the MFPs can be bypassed and the full pumping speed of both LDPs can be used for torus pumping.

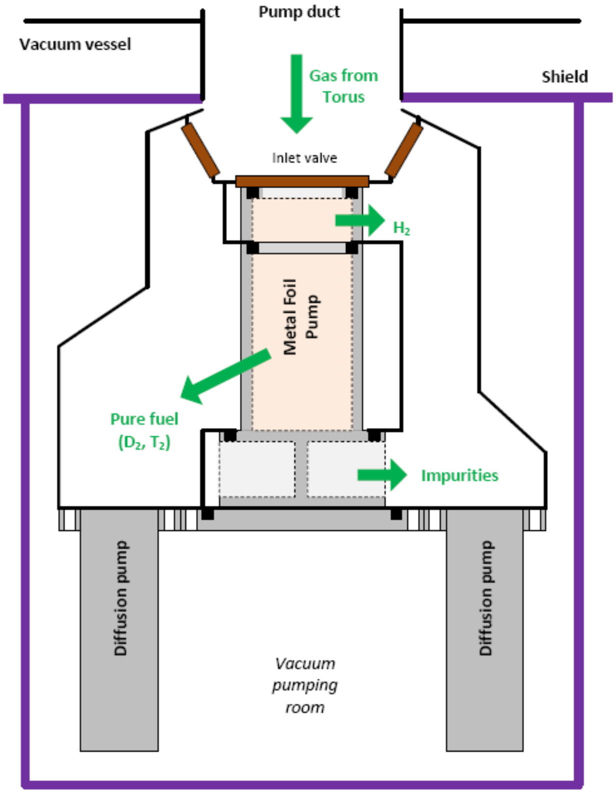


Fig. 62: Sketch of a pumping system installed on a pumping duct.

The sketch presented in Fig. 62 shows a very early pre-conceptual design. As next step, the pumping requirements (throughput, pressure and outgassing during burn and dwell etc.) as well as the pump performance for LDPs and MFPs must be assessed. Once these information is available, a simulation of the vacuum gas flows through pumps, duct and divertor must be done to come up with a conductance optimized design.

7. Future work

A two-stage liquid ring pump in DEMO relevant scale has never been built in the mercury and tritium compatible design and operated under fusion-relevant conditions. In order to select this pumping system for DEMO, it is absolutely necessary to gain operational experience and validate the design experimentally. A good opportunity for this exercise is the next deuterium-tritium experiment at JET. It is currently foreseen to install such a pumping system at JET and test it with tritium [93]. A detailed design has already been developed and the set-up of the system has been started. The commissioning of this system, called MTPS (Mechanical Tritium Pumping System), is currently foreseen for 2017. Once the tests in the THESEUS facility at KIT have been successful, it will be shipped to UK and an installed in the Active Gas Handling System (AGHS) at JET. In the following years, extensive testing will be done to gain information on this pumping system. Especially the reliability of the ceramic bearings running in liquid mercury and the cooling performance by the pump cooling jackets has to be demonstrated. If everything works as expected, a high technical readiness level can be reached on which basis the selection of this technology for DEMO can be done. It must be noted that for MTPS, also a mercury booster pump will be included that allows lower ultimate pressures for the roughing system. Here, a commercially available booster (EDWARDS 4B4B) has been used and modified towards tritium compatibility and for mercury as working fluid. The working principle of this booster is very similar to the diffusion-ejector pump considered for DEMO primary pumping, but the shape and the technical set-up is not relevant for the DEMO primary pumps. However, it is hoped that information on the operation of such a pump helps in the development of the LDP for DEMO and provides a solution if it is found that the rough pumping system has to reach lower ultimate pressures (< 0.1 Pa).

A linear mercury diffusion pump, based on the conceptual design presented in chapter 6.2.2, is under development at KIT. The design shall be already fully tritium compatible (to allow tritium operation in the TLK to gain operational experience) and, at the same time, very flexible to allow parametric studies in THESEUS (before tritium operation starts). Especially important for this development is a proper FEM analyses of the stresses in the pump under different operating conditions like normal operation, bake out (at 150°C and a corresponding high pressure in the water cooling plates) and in case of a safety event (internal explosion of an oxygen-hydrogen mixture followed by a pressure raise to 10 bar(g)). It was found that the mechanical stresses in the pump, due to the different temperature levels in the pump, are difficult to handle and have a strong impact on the pump design. Fig. 63 shows the current design with supply pipes for the mercury vapour. Each linear diffusion stage, which is basically a pipe with a slit over the full length, can be exchanged for parametric studies. By replacing it towards a 'dummy pipe' the dependency of the pump performance on the number of stages can be investigated. For the mercury boiler, not shown in this figure, it is intended to use a very similar (electrical) boiler as already developed for the MTPS booster pump. This is fully sufficient for pump testing in a non-fusion environment. Later, when the detailed design work for DEMO will start, a design for a suitable boiler will be developed. This is not considered as a major problem that has to be addressed during the pump development process.

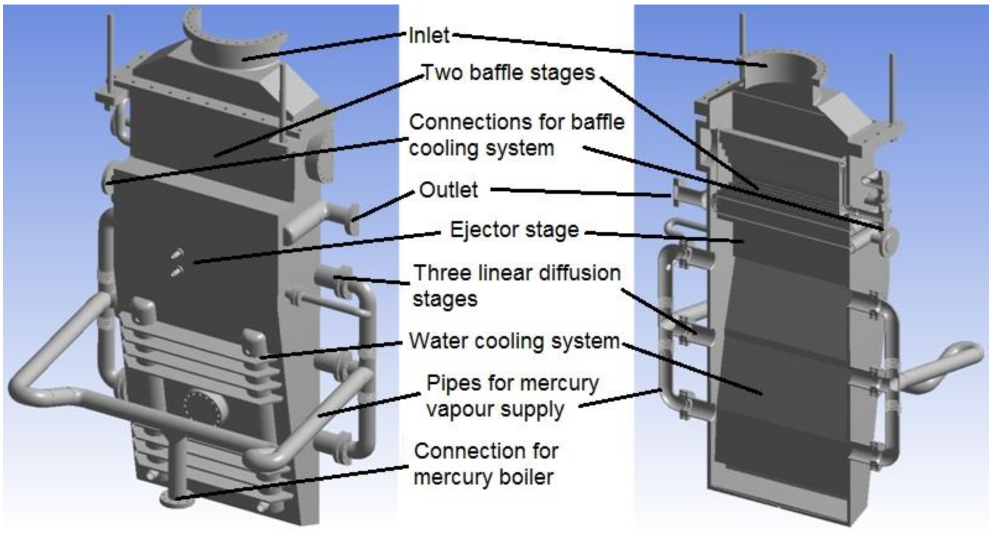


Fig. 63: The Linear mercury Diffusion Pump (LDP) currently under development at KIT.

To be able to test the pump in THESEUS, a significant infrastructure update is necessary. The baffle system needs to be supplied by gaseous nitrogen at 25 bar(g) at temperature levels of 180…200 K and 220…240 K, respectively. Also cool water has to be delivered at a variable temperature of 270…300 K. For bake out, the two gas circuits and the cool water circuits must be operated at 150°C. Before opening the linear diffusion pump (e.g. for changing the nozzles), it must be purged by hot nitrogen for removing all residual mercury towards a charcoal filter in the exhaust gas. Therefore, LDP infrastructure system, that is also considered to be fully DEMO relevant, is currently under development at KIT. Once the design development for the linear mercury diffusion pump is finalized, it will be built and installed in THESEUS. In parallel, the infrastructure system has to be set up, commissioned and tested. First results of the experiments are not expected before 2018.

Next step in the development of a DEMO relevant metal foil pump is the definition of the requirements on a prototype pump. Therefore, information are needed concerning

- Pumping performance of the metal foil
- Separating function of the foil
- Requirements on foil conditioning (operational temperature, heating method, regeneration needs etc.)
- Method for atomic hydrogen generation
- Maintenance requirements
- Space restrictions
- Infrastructure requirements
- Instrumentation & control requirements

In the next years, a R&D program will be launched at KIT with the goal to address all the unknowns mentioned above. The central test environment for the experiments will be the HERMES facility. As soon as enough information are available to design a prototype metal foil pump, a pump will be built in technical scale and tested in THESEUS.

Once the testing of the metal foil pump, the diffusion pump (incl. infrastructure) and the liquid ring pump (MTPS) is done successfully, a combination of all systems must be tested. Most important is the test of the combination between metal foil pumps and the diffusion pumps as these pumps have are responsible for gas separation (DIR) and machine pump-down during dwell. The combination between metal foil pumping and diffusion pumping is not easy to predict and has a very strong influence on design and size of the whole pumping system of the inner fuel cycle. As mid-term perspective, the test of a 1:4 scale DEMO pumping duct is highly recommended, e.g. in the THESEUS facility. An overview of the estimated size and performance of such an set-up is given in Tab. 15 (Case A) and compared with the estimated size and performance of a full-scale system (Case B). The results and experience obtained will be essential for design and operation/control of a pumping system for DEMO.

Tab. 15: Estimated size and performance of an experimental set-up, compared with the size and performance of a full-scale system.

	Case A (1:1 scale)	**Case B (1:4 scale in size, 1:8 in performance)**
Duct size (length x width), inner dimension	1.6 m x 0.8 m	0.8 m x 0.4 m
Max. pumping speed	25 m^3/s (= 100 %)	3 m^3/s (= 13 %)
Footprint of pumping system (length x width), excl. valve actuators	2 m x 2 m	1.2 m x 1.6 m
Duct height incl. diffusion pumps (below bioshield)	3.5 m	3.5 m
Location	E.g. in pump caves below the machine (below bioshield)	THESEUS facility at KIT
Inlet valve (number and size)	2 (DN630)	1 (DN320)
Bypass valve (number and size)	4 (DN320)	2 (DN160)
Metal foil pump size (diameter x length)	630 mm x 1500 mm	320 mm x 1500 mm
Diffusion pump size (length x width x height)	1.6 m x 0.4 m x 2 m	0.4 m x 0.4 m x 2 m
Opening area MFP inlet	0.62 m^2	0.08 m^2
Opening area LDP inlet	1.28 m^2	0.16 m^2
Opening area bypass valves (incl. MFP)	0.32 m^2	0.04 m^2

8. Summary and Conclusion

In this work, a novel vacuum pumping concept – the KALPUREX process – has been developed for the inner fuel cycle of DEMO, the first demonstration fusion power plant currently under development in Europe. This activity has become necessary after it was found in an assessment of currently available tritium processing methods that the scaling of these systems towards fusion power plants will most probably not be possible and has the potential to become a show-stopper.

The KALPUREX process is the technical realization of the Direct Internal Recycling (DIR) concept, developed to reduce the inventory of radioactive tritium in the inner fuel cycle of fusion power plants by introducing a shortcut between the pumping and the fuelling systems for unburned fuel (i.e. pure deuterium and tritium). If KALPUREX is applied, the tritium inventory in the inner fuel cycle will get much smaller what reduces safety and licencing issues and the problem of non-availability of enough tritium for machine start-up. Also a huge, expensive and complex-to-operate cryogenic facility is not needed anymore for vacuum pumping. The process is based on the combination of three pumping methods:

- Diffusion pumping for primary pumping,
- metal foil pumping, as part of the primary pumping system, to realize DIR and
- liquid ring pumping for rough pumping.

These three pumping methods have been identified using a theoretical approach (pairwise comparison, calculation of a quality rating, technological-economic examination), starting with a review of available methods for vacuum generation. After this identification process, described here in detail, it was checked if the identified pumping methods have ever been demonstrated to work under DEMO relevant conditions. Unfortunately, a number of gaps have been identified here, what asked for experimental validation activities.

For these proof-of-principle experiments, two new facilities, THESEUS and HERMES, have been designed, assembled, commissioned and operated. As result, it could be shown that all three pumping methods can be applied under DEMO relevant conditions.

Based on this positive outcome, a conceptual design for three vacuum pumps, applicable for the KALPUREX process, has been proposed:

- Linear mercury diffusion-ejector pumps as primary pumps
- Metal foil pumps as primary pumps
- Two-stage liquid ring pumps with mercury as working fluid

This work ends with a conceptual design proposal for the pumping system. In a next step, the detailed design development of the identified vacuum pumps must be started, accompanied by the development of simulation tools for the pumps to support the design activity. An overview on ongoing and planed activities in this field are also included in this work.

Appendix

A1 Literature on superpermeability

Title	Authors	Year	Metal foil	Atomizer	Medium	Pressure	Maximum Flow	Content
Tritium Superpermeability: Experimental investigations and simulation of tritium recirculation in "Prometheus" setup	R.K. Musyaev, B.S. Lebedev, S.K. Grishechkin, A.A. Yukhimchuk, A.A Busnyuk, M.E. Notkin, A.A. Samartsev, A.I. Livshits	2005	Cylindrical niobium membrane (100 mm diameter, 180 mm height, 0.1 mm thickness)	Total area 120 cm^2 three separate tantalum ribbons up to 2300 K	Protium, deuterium, tritium	Factor 10^3 From 0.003 Pa to 0.3	2.5 l/cm^2s for protium 1.8 l/cm^2s for deuterium 1.5 l/cm^2s for tritium	- Demonstration of recirculation and separation effects - Calculation of tritium inventory in the membrane - Pumping rate is inversely proportional to the square root of the isotope mass
Hydrogen superpermeable membrane operation under plasma conditions	M. Bacal, A.M. Bruneteau, A.I. Livshits , V.N. Alimov , M.E. Notkin	2003	Two tubular membranes of niobium and vanadium (1 cm diameter, 18 cm long, 0.01 cm thick)	16 tantalum filaments located close to the chamber wall in the multicusp magnetic field; chamber wall serving as an anode; 60 V/30 A discharge at 2-5 mTorr; plasma density 10^{10}-10^{11} cm^{-3}, electron temperature 0.5-1 eV	Protium	2-5 mTorr	-	- Membrane temperature from 910-1420 K, no effect of sputtering at 1420 K - Bias from 0 – 250 V - Membrane doping with oxygen reduces effects of ion bombardment - Decarbonization leads to a membrane state resistant to sputtering up to 1 keV - Low oxygen mobility in Nb-carbide
Influence of oxygen and carbon on performance of superpermeable membranes	Y. Hatanoa, A. Livshitsb, Y. Nakamurac, A. Busnyukb, V. Alimovb, C. Hiromia, N.Ohyabuc, K. Watanabea	2005	Nb, V, (Ta)	Discussion of atomizer and plasma	Protium	-	-	- Investigations on C/O chemisorbed monolayers and thin films of oxide and carbide
Anomalous isotope effect in the	A. I. Livshits, M. E. Notkin, and M.	2002	Resistively heated tubular membrane of	-	-	-	2-3 x10^{16} $1/(cm^2s)$	- Sharp decrease of deuterium permeation at 910 K and E = 30-

permeation, retention, and reemission at interaction of energetic hydrogen with niobium	Bacal		Nb (1 cm in diameter, 18 cm long, with a 0.01 cm wall thickness)					60 eV - Mathematical discussion of sputtering and oxygen dissolution - Low temperatures lead to a strong anomalous isotope effect
Development of divertor pumping system with superpermeable membrane	Y. Nakamura, N. Ohyabu, H. Suzuki, Y. Nakahara, A. Livshits, M. Notkin, V. Alimov, A. Busnyuk	2000	Cylindrical Nb membrane with the surface area of 1000 cm^2	Set of incandescent tantalum wires (full surface area 200 cm^2) linear plasma device (TPD) 10 eV and a density of 10^{13} cm^{-3} $n_{e-}=10^9$ 10^{10} cm^3, T_e in a few eV, p (H_2)=10^2Torr	Protium, deuterium; in reactor	10^3	10^3 l/s 3x 10^{17} H/(cm^2s) (atomizer)	- Long-term stable operation of the membrane pumping system (40 h) with a hydrogen plasma - Membrane installed into divertor of JFT-2M - Superpermeation degradation (Fe and C) disappears at T>800°C - Sputtering and impurity deposition has been observed
Fuel recycling and edge plasma control with membrane techniques: plasma and membrane simulation experiments	A. Livshits, N. Ohyabu, M. Bacal, Y. Nakamura, A. Busnyuk, M. Notkin, V. Alimov, A. Samartsev, H. Suzuki, F. Sube	1999	Nb, V	Few plasma devices simulating different fusion machine conditions	Protium	-	2x10^{17} 1/cm^2S	- Effects of impurity deposition vanish at temperatures > 750°C - Monolayer removed by way of chemical sputtering with hydrogen particles of an energy in the range of one to tens of eV - Discussion of 3 different plasma setups and atomizer - With “camembert” setup high permeation flux reached - Impurity deposition and effects on k_r with setup B - Scheme C for isolating hydrogen as impurity gas in helium plasma
Applications of superpermeable membranes in fusion: The flux density problem and experimental progress	A. Livshits, N. Ohyabu, M. Notkin, V. Alimov, H. Suzuki, A. Samartsev M. Solovyov, I. Grigoriadi, A. Glebovsky, A.	1997	Cylindrical Nb-membrane	-	-	3x10^{-2}Torr upstream pressure	3x10^{17} 1/cm^2s at high upstream pressure	- Pumping speed and permeation flux at various upstream pressures - Calculations on atomization probability - Whole campaign lasted ~ 2000h - No problems with water and oil

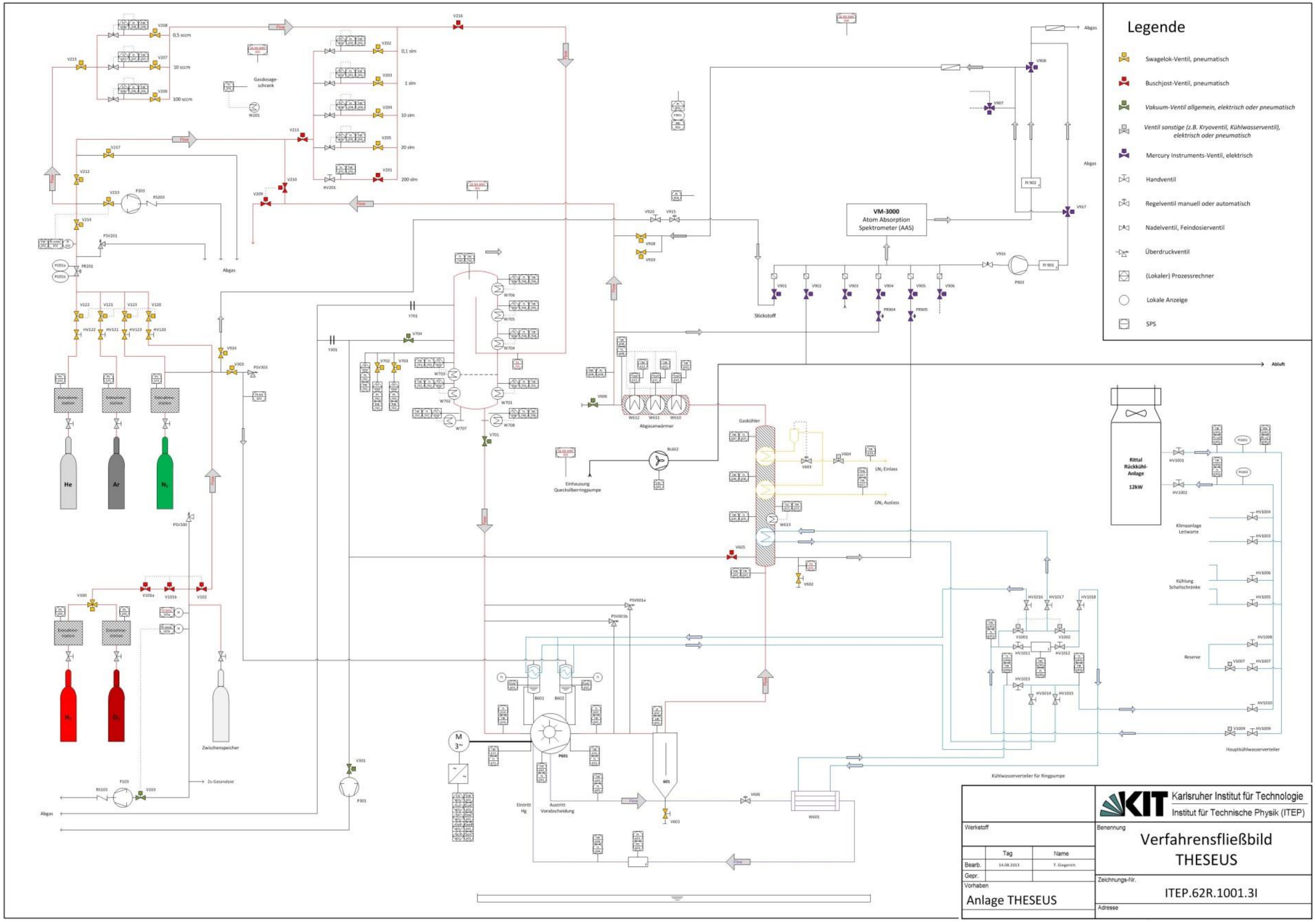
	Busnyuk, A. Doroshin, K. Komatsu							vapour - Higher flux density possible with better atomization and better TMP?
Superpermeability to fast and thermal hydrogen particles: Applications to the pumping and recycling of hydrogen isotopes	A.I. Livshits, M.E. Notkin, A.A. Samartsev, A.O. Busnyuk, A.Yu. Doroshin and V.I. Pistunovich	1992	0.1 mm thick Nb-membrane	V, Nb or T atomizer	Protium	Tests performed in UHV 10^3-10^4	1.5 l/cm^2s	- Schematic suggestion of superpermeable membranes to be used in the ITER ducts - 160 m^2 membrane area and 5 MW of power required to separate 75% of the mixture - At 10^3 compression: 5-10 g of tritium will be accumulated
Superpermeable membrane for particle control in divertor: The effect of impurity deposition	Y. Nakahara, Y. Nakamura, N. Ohyabu, H. Suzuki, A. Busnyuk, V. Alimov	2000	0.2-0.3 mm Nb-membrane (tubular)	Divertor membrane setup	Protium	UHV	-	- Carbon and stainless steel deposition on the membrane - At T_m>800°C all effects almost vanish - Membrane temperature lower than 800°C is proposed for a real fusion device due to lower impurity concentrations
Experimental study of membrane pump for plasma devices	H. Suzuki, N. Ohyabu, Y. Nakamura, A. Sagara, O. Motojima, A. Livshits, M. Notkin, A. Busnyuk,K. Komatsu	1998	A.S mm thick, 1000 cm^3 area, tubular Nb	Atomizer and plasma	Protium	Inlet: ~ 10^{-4} Torr (atomizer) ~$5x10^{-6}$ Torr (plasma)	$3x10^{17}$ H/cm^2s (atomizer) $5x10^{14}$ H/cm^2s (plasma)	- Permeation rate increases with discharge current (plasma) - High permeation flux for tantalum atomizer - Low permeation flux for plasma - Permeation probability about 5% for plasma
Effects of thin films on inventory, permeation and re-emission of energetic hydrogen	N. Ohyabu, Y. Nakamura, Y. Nakahara, A. Livshits, V. Alimov , A. Busnyuk, Notkin, A. Samartsev, A. Doroshin	2000		-	-	10^{-2} Torr	Incident:~ $5x10^{16}$ $4x10^{15}$ H/cm^2s	- Detailed investigation of carbon films - No problems with NbC - Carbide multilayer effects are suppressed at high (dissolution) and low temperatures (sputtering)
Plasma driven superpermeation of	A. I. Livshits F. Sube, M. N.	1998	Nb, V	Plasma	Protium	Upstream pressure 1,6mTorr	~$2x10^{17}$ H/cm^2s With plasma	- A lot of fundamental questions are answered - The density

hydrogen through group Va metals	Solovyev M. E. Notkin and M. Bacal					Compression up to 10^3		of hydrogen atoms is typically a few percent and greatly exceeds the ion density, rest hydrogen molecules - Campaign lasted for 300hs - Ions with energies around 10 eV may contribute to the membrane asymmetry - Critical sputtering energies at 50-70 eV
Superpermeability: Critical points for applications in fusion	A.I. Livshits, M.E. Notkin, V.I. Pistunovich, M. Bacal, A.O. Busnyuk	1995	0.1 mm Nb	Atomizer	-	10^3-10^4 (?)	$3x10^{16}$ H/cm^2s Simulation yielded $4x10^{17}$/cm^2s	- Calculations on maximum possible flow: 10^{19} H/cm^2s - Proposal for a membrane system to be installed in the ITER ducts - 3000 h experimental campaign
Physico-chemical origin of superpermeability – large-scale effects of surface chemistry on “hot” hydrogen permeation and absorption in metals	A.I. Livshits, M.E. Notkin and A.A. Samartsev	1990	-	-	-	-	-	- Calculations on permeation probability - Sources for data on metals needed for calculation - Superpermeation means permeation probability = 0,1…1 - Discussion of superpermeability origin: non-metal impurities (nonolayer)
Investigation of a large volume negative hydrogen ion source	C. Courteille, A. M. Bruneteau and M. Bacal	1995	-	Camembert III plasma device	-	-	-	- The plasma chamber used in the Livshits paper from 1998 is described - A plasma chamber is a complex setup - Multicusp magnetic field to reduce wall collisions - Plasma parameters as a function of discharge current
Impact of surface phenomena in metals on hydrogen isotope permeation	M. Yamawaki, N. Chitose, V. Bandurko, K. Yamaguchi	1995	Information on several metal, Nb-foil with 0.1 mm	-	-	10^{-4} Pa – 1 Pa	Permeation $2x10^{14}$ D/cm^2s IDP $9,4x10^{12}$ D/cm^2s	- Different definition of superpermeability in this paper - Some data on surface barrier presented

A Model for atomic hydrogen-metal-interaction- application to recycling, recombination and permeation	M. A. Pick and K. Sonnenberg	1985	-	-	-	-	-	- Calculations on k_r - Difference to Livshits: a factor for the surface occupation is given - Diffusion coefficients seem to be relevant
Annual report of Hydrogen Isotope Research Center, Toyama University	Y. Hatano, M. Nomura, K. Watanabe, A.I. Livshits, A. O. Busnyuk, Y. Nakamura, N. Ohyabu	2002	0.1mm Nb, information on preparation (laser welded) and joint tube heating to provide homogenous heat profile	Plasma and atomizer in one apparatus	Protium, Deuterium	-	Impact flux: 10^{17} atoms $cm^{-2}s^{-1}$ and 10^{15} ions/cm^2s (plasma) 10^{16} H/D/cm^2s atomizer	- Permeation with controlled surface state - Heating in UHV to clean surface - Values for activation energy - Permeation and superpermeation mixed
Nb interaction with hydrogen plasma	Y. Nakamura, A. Busnyuk, H. Suzuki, Y. Nakahara, N. Ohyabu et al.	2001	Nb membrane of 30 mm diameter, 150 mm length, and 0.3 mm thickness	Plasma apparatus electron temperature a few eV, electron density in the range of 10^9–10^{10} $cm^{-2}s^{-1}$	-	Upstream: 3 Pa	Incident ions: $3.3x10^{15}$ $cm^{-2}s^{-1}$, incident neutrals: 5-10x10^{16} H/cm^2s	- Sputtering - O doping - PDP calculated from experimental values of downstream pressure with plasma and downstream pumping - Sticking coefficients are evaluated - Sputtering calculations - No solution for ~10 eV branch
Permeation of hydrogen through palladium	J. Park, T. Bennett, J. Schwarzmann, S.A. Cohen	1995	Palladium, 0.1-1mm, 40-250 °C	Princeton Hyperthermal Atomic Beam (PHAB) facility 1 cm radius, cylindrical, pulsed (typically 5 ms duration, 5% duty factor), highly ionized hydrogen (H ÷) plasma,	-	Upstream: 1.2 Pa	Energy ~10eV Permeation flux: 2,6*10^{14} H/cm^2s	- Aspects of a DIR concept described - Atomizer has to be placed inside the duct - Criticizes first Livshits ideas

				formed by lower-hybrid heating at 2.45 GHz in a (~ 15 cm) cylindrical waveguide, flows ~ 20 cm along a 3.5 kG magnetic field onto a refractory metal plate				
Membrane pumping technology for helium and hydrogen isotope separation in the fusion reactor	V.I. Pistunovich, A. Yu. Pigarov, A.O. Busnyuk, A.I. Livshits, M.E. Notkin, A.A. Samartsev, K.L. Borisenko, V.V. Darmogray, B.D. Ershov, L.V. Filippova , B.G. Mudugin, V.N. Odintsov, G.L. Saksagansky, D.V. Serebrennikov	1995	600 cm^2 cylindrical Nb membrane	Nb and Ta ribbon atomizer	-	P_out <= $3*10^{-1}$ Torr	-	- Suggestion for a pumping module with many charts - Again the suggestion for a ITER metal foil pumping system - Estimation for 90% and 98% separation: 5-9.5 MW
Superpermeability in fusion technology: tritium accumulation and compression	A. I. Livshits, Yuji Hatano, K. Watanabe	2002	-	-	-	-	-	- Good introduction pointing out benefits of metal foil - All flux are atomic flux so k_r = $2xk_r$ and alpha = 2* alpha!

A2 Flowchart of the THESEUS facility



A3 List of publications

#	Year	Type	Reference
1	2010	Talk	S. Varoutis, S. Misdanitis, S. Pantazis, V. Hauer, T. Giegerich, C. Day, D. Valougeorgis **Experimental and numerical investigation of vacuum gas flows in fusion vacuum systems** 26th Symp. On Fusion Technology (SOFT), Porto, Portugal
2	2010	Talk	S. Varoutis, S. Pantazis, T. Giegerich, C. Day, D. Valougeorgis **Experimental and numerical investigation of vacuum gas flows through tubes with sudden expansion or contraction** 11th Europ. Vacuum Conf. (EVC), Salamanca, Spain
3	2011	Inv. Talk	C. Day, T. Giegerich, V. Hauer, X. Luo, F. Sharipov, S. Varoutis, D. Valougeorgis **Recent developments in vacuum flow modelling** Int. Vacuum Congress, Beijing, China
4	2011	Inv. Talk	C. Day, T. Giegerich, S. Hanke, V. Hauer, R. Lässer, S. Papastergiou **Design development of cryopumping systems for ITER in view of future DT fusion devices** 10th Int. Symposium on Fusion Nuclear Technology (ISFNT), Portland, OR, US
5	2011	Talk	T. Giegerich, C. Day, V. Hauer **Development of a tritium compatible vapour diffusion pump for a commercial fusion power plant** 10th Int. Symp. On Fusion Nuclear Technology (ISFNT), Portland, OR, US
6	2011	Talk	T. Giegerich, S. Varoutis, V. Hauer, C. Day **Measurements in the TRANSFLOW facility** 64th IUVSTA Workshop on Practical Applications and Methods of Gas Dynamics for Vacuum Science and Technology, Leinsweiler, Germany
7	2011	Talk	T. Giegerich, C. Day **View on challenges in operating fusion power plant vacuum systems** 3rd Workshop on the Operation of Large Vacuum Systems (OLAV), Oak Ridge, TN, US
8	2011	Talk	T. Giegerich, C. Day **Development of vacuum flow modelling tools** 3rd Workshop on the Operation of Large Vacuum Systems (OLAV III), Oak Ridge, TN, US
9	2011	Talk	R.C. Wolf et al. **Assessment of the physics and technology requirements for a fusion DEMO: Integration of Fusion Science and Technology for Steady State Operation** 21st Int. Toki Conf., Toki City, Gifu, Japan
10	2011	Inv. Talk	C. Day, D. Demange, T. Giegerich, V. Hauer, R. Wolf, V. Kotov, D. Reiter **An integrated view on high density operation and fuel cycle** MFE Roadmapping Workshop, Princeton, NJ, US

11	2011	Inv. Talk	C. Day, T. Giegerich, S. Hanke, V. Hauer, M. Scannapiego, S. Papastergiou, R. Lässer **Design development of cryopumping systems of ITER in view of future DT fusion devices** Int. Symp. On Fusion Nuclear technology (ISFNT), Portland, OR, US
12	2011	Inv. Talk	C. Day, T. Giegerich, H. Haas, V. Hauer, S. Hanke, X. Luo, S. Varoutis, **Modelling and simulations of the ITER cryopumping systems** Annual Symposium of the American Vacuum Society, Nashville, TN, US
13	2012	Talk	C. Day, T. Giegerich, V. Hauer **A network modelling approach for complex vacuum systems in a wide range of the Knudsen number** 27th Symp. On Fusion Technology (SOFT), Liege, Belgium
14	2012	Talk	C. Day, B. Bornschein, D. Demange, T. Giegerich, M. Kovari, B. Weyssow, R. Wolf **Technology gaps for the fuel cycle of a fusion power plant** 24th Fusion Energy Conf., San Diego, CA, US
15	2012	Talk	C. Day, T. Giegerich, V. Hauer, X. Luo, S. Varoutis **The use of flow network tools for geometrically complex vacuum gas dynamics problems** 6th European Congress on Computational Methods in Applied Sciences and Engineering (ECCOMAS), Vienna, Austria
16	2012	Talk	T. Giegerich, C. Day **Fusionskraftwerke – Anforderungen und gegenwärtige technische Entwicklungen der Vakuumpumpsysteme** Frühjahrstagung DPG, Sektion Kondensierte Materie, Fachverband Vakuumphysik und Vakuumtechnik, Regensburg, Germany
17	2012	Talk	X. Luo, T. Giegerich, C. Day **Transient gas flow studied by test particle Monte Carlo approach with ProVac3D** 28th Int. Symp. On Rarefied Gas Dynamics (RDD), Zaragoza, Spain
18	2012	Paper	S. Varoutis, T. Giegerich, V. Hauer, C. Day **TRANSFLOW: an experimental facility for vacuum gas flows** Journal of Physics: Conference Series 362 012027
19	2012	Inv. Talk	C. Day, T. Giegerich, V. Hauer, X. Luo, S. Varoutis **The use of flow network tools for geometrically complex vacuum gas dynamics problems** 6th Europ. Congress on Computational Methods in Applied Sciences and Engineering (ECCOMAS), Vienna, Austria
20	2013	Talk	C. Day, T. Giegerich **Exhaust pumping of DT fusion devices – Current state-of-the-art and a potential roadmap to a power plant** 25th Symp. On Fusion Engineering (SOFE), San Francisco, CA, US

21	2013	Inv. Talk	C. Day, T. Giegerich **Non-cryogenic pumps for DEMO** 21st Congress 'Materials, Interfaces, Processes: New Challenges for Future Applications', Catania, Italy
22	2013	Paper	C. Day, T. Giegerich **The Direct Internal Recycling concept to simplify the fuel cycle of a fusion power plant** Fusion Engineering and Design, 88 pp.616-620
23	2013	Talk	T. Giegerich, C. Day **A metal foil vacuum pump for the fuel cycle of fusion power plants** Frühjahrstagung DPG, Sektion Kondensierte Materie, Fachverband Vakuumphysik und Vakuumtechnik, Regensburg, Germany
24	2013	Paper	T. Giegerich, C. Day **Conceptuation of a continuously working vacuum pump train for fusion power plants** Fusion Engineering and Design 88 pp.2206–2209
25	2013	Talk	T. Giegerich, C. Day **The THESEUS facility – A test environment for the torus exhaust vacuum pumping system of a fusion power plant** 25th Symp. On Fusion Engineering (SOFE), San Francisco, CA, US
26	2013	Talk	T. Giegerich, C. Day **Theoretical and experimental investigation of metal foil vacuum pumps for pumping and separating hydrogen** 19th International Vacuum Congress (IVC), Paris, France
27	2013	Talk	X. Luo, T. Giegerich, C. Day, **Monte Carlo simulation of a vapour diffusion pump** 19th Int. Vacuum Congress (IVC), Paris, France
28	2013	Paper	X. Luo, T. Giegerich, C. Day **Transient gas flow studied by a test particle Monte Carlo approach with ProVac3D** 28th Int. Symp. On Rarefied Gas Dynamics (RDG), Zaragoza, Spain AIP Conference Proceedings 1501 Vol.1 pp.857–863 ISBN 978-0-7354-1116-6
29	2014	Paper	C. Day, T. Giegerich **Development of advanced exhaust pumping technology for a DT fusion power plant** IEEE Transactions on Plasma Science 42 pp.1058-1071
30	2014	Paper	T. Giegerich, N. Bekris, B. Butler, C. Day, M. Gethins, S. Lesnoj, R. Müller, S. Ochoa, P. Pfeil, R. Smith **Conceptual design of the DEMO relevant liquid ring pump train for JET DTE2** Accepted for Publication in Fusion Science and Technology.

31	2014	Talk	T. Giegerich, C. Day **Hydrogen ion driven permeation for vacuum pumping** 12th Int. Workshop on Hydrogen Isotopes in Fusion Reactor Materials, Toyama, Japan
32	2014	Inv. Talk	T. Giegerich, C. Day, X. Luo, R. Müller, S. Ochoa, M. Scannapiego, H. Strobel **Revival of mercury diffusion pumps – A new, compact design for fusion applications** Frühjahrstagung DPG, Sektion Kondensierte Materie, Fachverband Vakuumphysik und Vakuumtechnik, Regensburg, Germany
33	2014	Paper	T. Giegerich, C. Day **The KALPUREX-Process – A new vacuum pumping process for exhaust gases in fusion power plants** Fusion Engineering and Design 89 pp.1476-1481
34	2015	Paper	T. Giegerich, N. Bekris, B. Butler, C. Day, M. Gethins, S. Lesnoj, R. Müller, S. Ochoa, P. Pfeil, R. Smith **Advanced design of the DEMO relevant liquid ring pump train for JET DTE2** Submitted for publication in: Proc. Of the Int. Symp. On Fusion Nuclear Technology (ISFNT), Jeju Island, South Korea
35	2015	Paper	P. Batistoni, D. Campling, S. Conroy, T. Giegerich, X. Lefebvre, I. Lengar, S. Lilley, M. Pillon, S. Popovichev, S. Reynolds, R. Vila, R. Villari, N. Bekris **Technological exploitation of Deuterium-Tritium operations at JET in support of ITER design, operation and safety** Submitted for publication in: Proc. Of the Int. Symp. On Fusion Nuclear Technology (ISFNT), Jeju Island, South Korea
36	2015	Talk	X. Luo, C. Day, T. Giegerich **Simulation of a Large Linear Jet Mercury Diffusion Pump with the Test Particle Monte Carlo Method** 19th Int. Vacuum Congress (IVC), Paris, France

A4 List of reports

Year	Report
2011	T. Giegerich, C. Day, D. Valougeorgis **Assessment of the pumping systems for DEMO** Report on EFDA Work Package WP11-DAS-HCD-FP-01/02 IDM Ref. EFDA_D_2M5S3W, 105 pages, December 2011
2012	T. Giegerich, X. Luo, C. Day **Investigation of candidate vacuum pumping systems** Report on EFDA Work Package WP12-DAS-05 IDM Ref. EFDA_D_2L98Y8, 122 pages, December 2012
2013	V. Day, T. Giegerich, X. Luo **Final Report on investigation of candidate vacuum pumping systems** Report on EFDA Work Package WP13-DAS05-D01 IDM Ref. EFDA_D_2M62PE, 69 pages, December 2012
2013	T. Giegerich **Betriebsregelungen der THESEUS-Anlage** 59 pages, October 2013
2013	T. Giegerich **Das Sicherheitskonzept der THESEUS-Anlage – Besondere Betrachtung des Betriebs mit Wasserstoff und Quecksilber und Störfallanalyse** 79 pages, October 2013
2013	T. Giegerich, C. Day **DEMO system integration study of vacuum pumping systems** Report on EFDA Work Package WP13-SYS03-D04 IDM Ref. EFDA_D_2MGBKD, 24 pages, December 2012
2013	T. Giegerich **Betriebsregelungen des Plasmaexperiments HERMES – Besondere Betrachtung des Betriebs mit Wasserstoff und Deuterium** incl. Störfallanalyse, Explosionsschutzdokument und Gefährdungsbeurteilung incl. Sicherheitsdatenblätter und Arbeitsanweisungen 74 pages, September 2013
2015	T. Giegerich, M. Gethins, R. Müller, P. Pfeil, H. Strobel, H. Stump **Report on the detailed tritium compatible LRP pump design** Report on EUROfusion Deliverable TFV-V-JET-20-D01 IDM Ref. EFDA_D_2KZZNA, v2.0, 117 pages, June 2015
2015	T. Giegerich **MTPS detailed design documentation: Design description document for the Mechanical Tritium Pumping System (MTPS) for JET/AGHS** 101 pages, January 2015

A5 List of supervised student research projects

#	Year	Type	Author	Title
1	2011	Seminar Paper	Roland Richter	Erstellung eines Programms zur Auslegung und Validierung von Vakuumsystemen beliebiger Komplexität auf Server – Client Basis
2	2012	Bachelor Thesis	Benedikt Peters	Characterization of mercury diffusion pumps as tritium compatible high vacuum pumps for future fusion reactors
3	2012	Bachelor Thesis	Daniel Fischer	Investigation of superpermeable metal foils for the pumping system of fusion power plants
4	2013	Bachelor Thesis	Michael Mai	Calculation of a multistage gas cooler for the cleaning of waste gas by mercury ring pumps
5	2013	Bachelor Thesis	Yannick Hörstensmeyer	Simulation of low pressure mercury gas flows through the nozzle system of mercury diffusion vacuum pumps
6	2013	Diploma Thesis	Yannik Ille	Untersuchung eines Versuchsstandes zur Charakterisierung von superpermeablen Metallfolien mittels Wasserstoffplasma
7	2013	Diploma Thesis	Raoul Tchoumbe	Berechnung und Untersuchung notwendiger Modifikationen für den Einsatz von Quecksilberring-Vakuumpumpen in der Fusion
8	2014	Bachelor Thesis	Oliver Linder	Investigation of RF Plasma and Metal Foil Pumping for the Fuel Cycle of Fusion Devices
9	2014	Bachelor Thesis	Kimo Toema	Experimental investigation of superpermeable metal foils in the HERMES experiment
10	2015	Bachelor Thesis	Stefanie Blust	Gas flow balancing for the DEMO inner fuel cycle
11	2015	Bachelor Thesis	Nadin Osman	Investigation of Lithium-6 issues for nuclear fusion applications

A6 List of patents and awards

Year	Type	Reference
2014	Patent	T. Giegerich, C. Day **Verfahren und Vorrichtung zur kontinuierlichen Wiederaufbereitung von Abgas eines Fusionsreaktors** DE 102013109778.2 WE PCT/EP2014/002342
2014	Award	T. Giegerich, C. Day **1st European Prize for Innovation in Fusion Research** Awarded by the European Commission on the 28th Symposium on Fusion Energy (SOFT), September 30, San Sebastian, Spain.

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