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Preliminary configuration of the torus vacuum pumping system installed in the DEMO lower port

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In the European DEMO program, the design development of the demonstration power plant (DEMO) is currently in its pre-conceptional phase. This work includes also the design development of the vacuum vessel, where lower ports are important appendices that house the primary vacuum pumping systems as major components of the vacuum pumping and fuel processing systems. This paper develops a preliminary design configuration of the primary pumping systems. It starts with a definition of requirements on which basis the design of this so-called 'pump cask design' is evolved. Furthermore, this paper states clearly what work is required in order to come up with a sound pre-conceptional design for DEMO in 2020 and a conceptional design in 2027.

1. Introduction

According the KALPUREX process, currently under development at KIT, Metal Foil Pumps (MFPs) and Linear Diffusion Pumps (LDPs) are used for primary pumping: The MFPs provide a gas separation and split the reactor exhaust gas into an unburnt fuel gas flow (i.e. pure hydrogen gas) and a residual gas flow (hydrogen plus helium and impurities). Both flows are being further compressed and pumped by LDPs. This separation allows the recycling of the unburnt fuel directly back into the reactor (Direct Internal Recycling, DIR), reducing the tritium inventory significantly by bypassing the tritium plant.

For the design development of the DEMO vacuum pumping system [1] – especially for the design of the primary pumps inside the lower ports – two aspects have to be considered: Firstly, he whole vacuum pumping equipment installed inside the ports has to be handled remotely. This requirement has not only a strong effect on the design and configuration of the vacuum pumps itself, but also on other components installed inside the ports (e.g. pipework) and on the design of the remote maintenance systems. This is being described in chapter 2 and leads to the proposal of a first preliminary pump cask design described in chapter 3.

Secondly, The distance between vacuum pump inlet and the sub-divertor region has a strong influence on the conductance and, thus, on the required size of the pumps and/or the achievable pressure in the sub-divertor region. This has been studied, based on the first preliminary pump cask design, by using the Monte-Carlo code ProVac3D [2] to quantify the influence of different distances between sub-divertor region and pump inlet.

This Monte-Carlo approach has also been used to investigate the effect of MFPs in different configurations: These kind of pumps are assumed to be in a tubular design, where the gas enters from one side and the hydrogen penetrates the metal foil walls, whereas the residual gas leaves the tube on the rear side. To tailor the MFP on its required performance in the DIR concept [3], i.e. pumping speed and fuel – residual gas ratio, it might become necessary to vary the length over diameter (L/D) ratio of the MFP. The influence of this effect on the given preliminary pump cask design has also be simulated by ProVac3D and is described in chapter 4.

2. Requirements for primary pump integration

2.1 Performance requirements

Most important for the development of a preliminary configuration for the vacuum pumping system is the flow rate of the gas that has to be processed (i.e. first pumped and separated by the MFPs, later further compressed by the LDPs) and the pressures that have to be achieved after a given pump-down time. These requirements are summarized in Table 1.

It must be noted that these requirements are still floating and depend strongly on the chosen plasma scenario, the efficiency of the fuelling systems and the adjusted DIR ratio. However, for this work, the values presented here are assumed to be realistic [4]. To keep the number of ports equipped with vacuum pumping systems small, it should be envisaged to provide as much pumping speed as possible per pump port. This is especially relevant when considering that not all of the currently foreseen 16 lower ports (EU-DEMO 2017 baseline model) will be available for vacuum pumping (some will be blocked by e.g. diagnostics or remote maintenance tools).

Table 1. Performance requirements of the DEMO primary vacuum pumping system.

Estimated values for	Dwell phase	Burn phase
Duration	600-1000 s	7200 s (=2 h)
Lowest pressure	1-2 mPa (end of phase)	3 Pa (during phase)

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Gas throughput	0.1 Pa m^3/s*	448 Pa m^3/s
Pumping speed required	100 m^3/s (effective)	130 m^3/s (effective)

** Depending on machine wall outgassing*

2.2 Vacuum compatible design requirements

For a sound vacuum design, the vacuum pumps installed in the lower ports should face directly towards the sub-divertor region (where the gas molecules accumulate after passing the divertor openings). In an ideal case, the divertor openings and the pump openings are in direct alignment. This is important in order to keep conductance losses, i.e. the resistance of the flowing gas molecules, low. For the same reason, it is also important to keep the distance between pump inlet and sub-divertor region short and to avoid the blocking of this interspace by pipework. If the conductance loss is high, a major part of the installed pumping speed will be lost and does not contribute to pumping the torus, leading to a very inefficient pumping.

2.3 Infrastructure requirements

Metal Foil Pumps and Linear Diffusion Pumps require some infrastructure for operation [1]: The MFPs in its current design (which is still evolving) need to be supplied by RF power and cooled by cooling water and pressurized gas (e.g. nitrogen or helium).

The LDPs need to be heated with a heat transfer fluid and cooled by cooling water. LDPs apply mercury as tritium compatible working fluid [1]. To trap mercury vapour inside the pumps, a one- or two stage baffle has to be installed, depending on the findings during the test of these pumps. Figure 1 shows the infrastructure requirements for the LDP, that is installed downstream the MFPs.

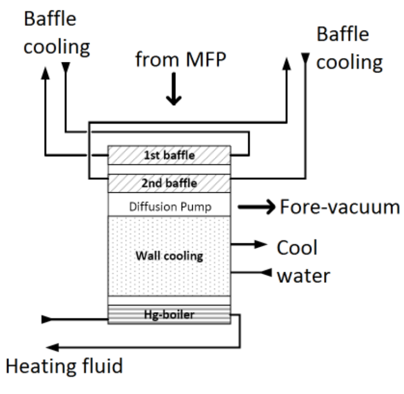

Fig. 1. Example of required infrastructure for the LDP.

The working assumptions for the infrastructure systems (pressure and temperature) are listed in Table 2 (slightly modified from [1]). According to the DIR concept [3], there will be two DIR circuits, i.e. ring lines that connect the primary vacuum pumps (MFP/LDP) with the fore-pumps (Liquid Ring Pumps as part of the tritium plant): One for the pure fuel and one for the residual gas. The actuator circuits are water hydraulic systems for operating e.g. the valves as part of the vacuum pumps.

Table 2. Estimated infrastructure and piping required for primary pumping.

Name and description of system	Connected to	Estimated pressure and temperature
Fore-vacuum (DIR circuit 1)	LDP 1	100 Pa, amb. temp.
Fore-vacuum (DIR circuit 2)	LDP 2	100 Pa, amb. temp.
Cool water, feed and return	LDP 1+2	2.5 MPa, amb. temp.
Baffle cooling, feed and return	MFP, LDP 1+2	2.5 MPa < 298 K
Heating fluid, feed and return	LDP 1+2	2.5 MPa < 200 K
Baffle 2nd stage cooling, feed and return*	LDP 1+2	2.5 MPa > 473 K
3 actuator circuits, feed and return	LDP 1+2	25 MPa < 240 K

** If required*

2.4 Requirements on remote operations

All primary pumping equipment has to be installed in a high radiation environment, close to the divertor. To guarantee a high availability of the machine, the number of remote operations and the time needed for each one must be reduced as much as possible. Therefore, it is desirable to combine the primary pumps that have to be installed in the lower port (MFPs and LDPs) as Line Replacement Unit (LRU). Main advantage of the LRUs is that they can be installed and removed without handling to many individual components.

The requirement on a LRU reflects the capabilities of the available remote handling tools and vice versa. It is thus important to consider the requirements from or on the Remote Maintenance (RM) systems from the very beginning of the design phase. This includes not only the components that have to be handled but also the electrical connections and the connections of all supply pipes. The design development of the vacuum pumps and its integration in the lower ports is thus a joint effort between the EUROfusion work packages Tritium – Matter Injection – Vacuum (TFV) and Remote Maintenance (RM).

3. Proposal of a primary pump integration scheme

The most promising option of combining MFP and LDP while fulfilling the requirements presented in chapter 2 is shown in Figure 2. Here, six MFPs (assumed as tube with 500 mm diameter and 2000 mm length) are installed in a box (green) that is connected to the two LDPs, each 2000 mm long, 600 mm width and 2’500 mm high, that provide the vacuum needed for MFP operation (red).

The LDPs are connected to the DIR circuits 1 and 2, respectively. To keep the size of the LRU as small as possible, the distance between MFP and LDP should be as low as possible. A rail system has to be foreseen as gravity support and to allow a well-defined installation of the pumping system inside the port.

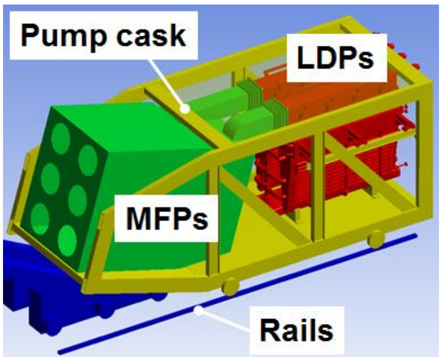

Fig. 2. Preliminary design of six MFPs and two LDPs combined in one 'pump cask'.

This so-called 'pump cask' acts as a LRU and can be installed using RM tools, as shown in Figure 3. To be compatible with the latest DEMO design, it is foreseen to connect the fore-vacuum lines to the DIR circuits 1 and 2 in the pipe chase from the front end of the pump cask, whereas the infrastructure connections (heating- and cooling fluids, electrical- and hydraulic connections) will be done from the rear side of the pump cask.

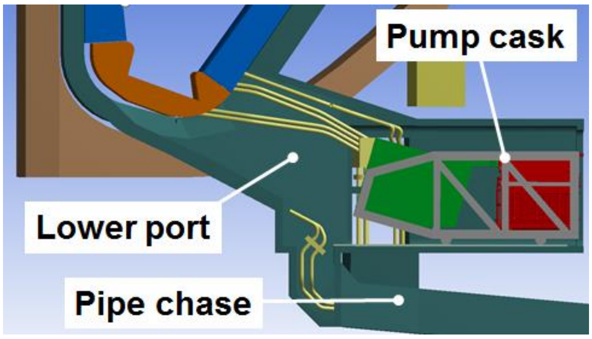

Fig. 3. Pump cask installed in the lower port, side view.

Special attention must be given to the pipework needed for divertor and/or blanket cooling: These pipes must not block the interspace between MFP inlet and sub-divertor region.

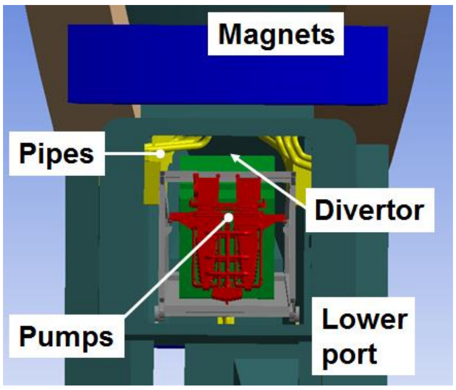

Fig. 4. Rear view of the lower port with pump cask installed.

4. Simulation of pump cask position

4.1 Description of the simulation approach

The conductance effect plays a major role in the design of the vacuum system. To investigate the influence of conductance losses caused by increased distances divertor – pump inlet, two different pump cask positions have been simulated (shown in Figure 5). The difference between the two positions Pos. 1 and Pos. 2 is 0.65 m.

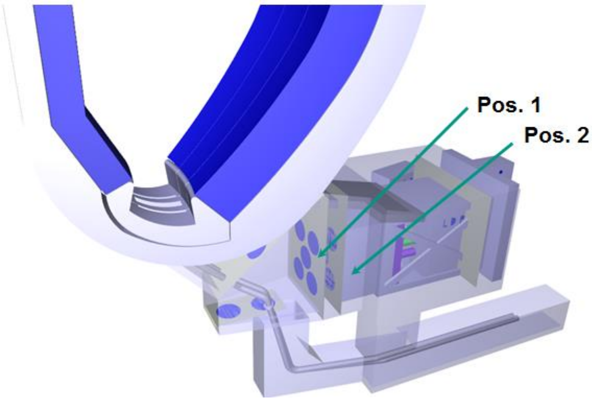

Fig. 5. The two positions of the pump cask inside the lower port as used for the simulation.

In a scoping study, different L/D ratios of the pumps in a tubular design have been investigated while keeping the front size of the pump cask constant. As 'lower case', a pump cask with 6 MFPs (and thus with a L/D ratio of 4) has been investigated, as 'upper case' a pump cask with 12 MFPs (and a L/D ratio of 8). Table 3 shows the two configurations used for simulation, representing the 'lower case' and the 'upper case'.

Table 3. Configurations used for simulation.

Configuration	Small L/D 'lower case'	Large L/D 'upper case'
Number of MFPs	6	12
Diameter of the MFP tube	0.5 m	0.25 m
Length of the MFP tube	2.015 m	2.015 m
L/D ratio	4.03	8.06
Total area of all tube openings	1.178 m^2	0.589 m^2
Total area of all tube pumping walls	19.0 m^2	19.0 m^2

For the simulation, the transmission probability of gas particles from the divertor to the MFP has been simulated by the Monte-Carlo code ProVac3D [2], assuming 10^{12} and 10^{11} deuterium molecules at a temperature of 300 K on the supercomputer Marconi at CINECA/Italy and FH2 at KIT, respectively. For the MFP, two different sticking coefficients for the gas particles have been assumed as boundary conditions: For the tubular metal foil, this value was 0.1, for the pump bottom (i.e. the outlet towards the LDP on the rear side), a value of 0.3 was assumed. The latter has been varied in a range between 0.1 and 0.7 and it was found that the effect has only a neglectable influence on w.

4.1 Simulation results

As result of the simulation, a transmission probability w for the deuterium molecules from divertor openings to and through the MFP has been be calculated. By multiplying w with the ideal (i.e. the maximum possible) pumping speed per divertor opening area, an effective pumping speed S could be calculated. The values given in Table 4 show that the effect of different pump positions (Figure 5) plays a minor role and can be neglected, while it is highly desirable to keep the L/D ratio small (and thus the MFP opening area large) in order to reach a high pumping speed for each pumping cask.

Table 4. Simulation results (overall transmission probability and resulting pumping speed) for four different cases.

	Transmission probability w	Pumping speed S
Pos. 1, small L/D	0.1396	128 m³/s
Pos. 1, large L/D	0.0828	76 m³/s
Pos. 2, small L/D	0.1390	128 m³/s
Pos. 2, Large L/D	0.0826	76 m³/s

5. Conclusions and outlook

This paper presents a preliminary configuration of the torus vacuum pumping system that is based on a pump cask that can be handled remotely and acts as a Line Replacement Unit. In the pump cask, Metal Foil Pumps (MFPs) in a tubular design will be installed inside a box connected to a frame structure that will be installed inside the lower port in a way it faces towards the divertor.

As the MFPs provide a gas separation function (required for the DIR concept [3]), two gas flows have to be extracted from the MFPs and transported (via Linear Diffusion Pumps, LDPs) to the fore-vacuum pumps, that are located in the tritium plant. The two fore-vacuum lines are ring lines and included in the pipe chase below the lower port, whereas the pump service connections are guided via the closure plate in the rear part of the pump cask through the port cell.

For the design of the torus vacuum pumping system, it is essential that the interspace between MFP opening and divertor is not blocked. The distance MFP opening-divertor plays only a minor role, as long as changes are in the decimetre range. This could be demonstrated using Monte-Carlo simulations. For the design of the MFPs a solution with a large inlet surface should be envisaged, what can only be reached if the L/D ratio is small. This asks for a good gas separation performance of the MFP.

To demonstrate the feasibility of this preliminary configuration, as well as the expected performance, a dedicated work programme is needed: The performance of MFPs and LDPs has to be known precisely, as well as the infrastructure requirements. This makes the development and testing of technical scale prototypes necessary.

For MFP and LDP, these developments have already been started in the EUROfusion work package TFV, where first results important for the scalability of the components will become available in 2019/2020. (Promising lab-scale experiments are already available [5-6].) With this result, it will be possible to elaborate a pre-conceptional design of the DEMO primary pumping system in 2020.

The period 2020 to 2027 should continue MFP and LDP development and combine the pumps to one pump cask, considering the findings of the pre-conceptional design phase and the special requirements for remote maintenance. This pump cask can then be tested as fully integrated demonstration unit. The results, expected for 2027, will be the basis for the following DEMO engineering design activity.

Acknowledgments

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