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Initial integration concept of the DEMO lower horizontal port

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The realisation of a Demonstration Fusion Power Reactor (DEMO) is the remaining and crucial step towards the exploitation of fusion power. This is the shared view of Europe and the nations engaged in the construction of ITER. DEMO will follow ITER and must be capable to produce several hundred MW of net electricity as well as operating with a closed fuel-cycle. The DEMO machine has three main entrance levels to the plasma chamber. According to the current DEMO reference configuration the vacuum vessel has 16 vertical upper, horizontal equatorial, and horizontal lower ports, respectively.
This article introduces the initial integration concept of the lower port. The concept considers the external space constraints, the neutron shielding requirements of the superconducting coils, and its functions. The latter support the vacuum vessel, host different systems, in particular the torus vacuum pump, and feeding pipes of in-vessel components, and allow for divertor remote maintenance. The size and position of the lower port are constrained by the adjacent toroidal and poloidal field coils. At the same time the lower port drives the layout of the cryostat and the tokamak building.

Keywords: Lower configuration port, divertor configuration port, divertor replacement

1. Introduction

The lower port, also named divertor, is positioned in the bottom of the tokamak machine. The port fulfils several functions in the machine and influences the arrangement of the in-vessel components. The three functions are in nature structural and operational and cover maintenance tasks. Supporting the vacuum vessel on the pedestal ring is the main structural purpose. The main operational functions of this port are to provide primary vacuum and to host the torus vacuum pumping unit, which consists of the metal foil pump and the linear diffusion pumps. the latter include all connected pipework such as fore-line, mercury circuit and electrical supply … [1]. In addition, the lower port must provide an adequate pumping duct from the sub-divertor region to the torus vacuum pump. Also the in-vessel components feeding pipes, i.e. outboard and inboard breeding blanket lithium lead pipes and divertor cooling water pipes must be integrated in the lower port. Their number and size depends on the breeding blanket concept either being water cooled lithium lead or Helium cooled peddle bed. Several maintenance functions have to be performed via this lower port: Divertor replacement, pipe cutting, joining and handling, and potential remote maintenance of additional systems such as diagnostics, gas injection or inspection tools.
The lower port design is not solely driven by its functions but also defined by space constrains and technical requirements. Three additional aspects come into play: Firstly, the internal space requirements are mainly due to the size of the divertor cassettes and their extraction kinematics considering also the necessary remote maintenance devices which operate inside the port. Secondly, the sizes of the torus vacuum pump unit also considering its remote maintenance scheme. Thirdly, the number and size of pipe work that needs to be removed prior to divertor remote maintenance. It is aimed at minimizing the latter and keeping them as permanent structures if not prevented by the limited port size.
The necessary internal dimension of the opening of the port towards the vessel is defined by the need to access the back surface of the in-vessel components to install the feeding pipes [5]. A crucial point in the design of the lower port is the provision of sufficient shielding of the toroidal field coils against nuclear heating since the port opening is a penetration of the main DEMO shielding structure, the vacuum vessel body. Also, gamma radiation streaming during shutdown from the activated in-vessel components through the port cell where man-access may be required must be limited by suitable shielding structures inside the lower port [5]. The configuration of the DEMO lower port also separates cooling water and lithium lead pipes from areas (port cell) foreseen for man-access (during shutdown and when the port is not opened up for maintenance) since radioactive isotopes emit neutron and gamma radiation from these pipes, as similarly predicted for ITER [2].

2. Former vertical lower port configuration

The previous lower port of the DEMO machine had a dedicated vertical port for the torus pumps whereas the main lower port was reserved for the replacement of the divertor. This port was inclined with a 45° angle. The consequences of this configuration on the adjacent

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systems, on internal pipework, and on the building layout had however not been assessed at that time. Recently, the following critical aspects were identified:

- Cross section of pumping port too small for efficient operation of the torus vacuum pump
- Pipe work to inboard blankets obstruct pumping path
- Steep angle of lower port decreases the port cross section due to smaller distance between toroidal field coils, see Figure 2
- Vertical pump duct clashed with tokamak support structure and space required for magnet feeders, in particular for central solenoid and poloidal field coil 1

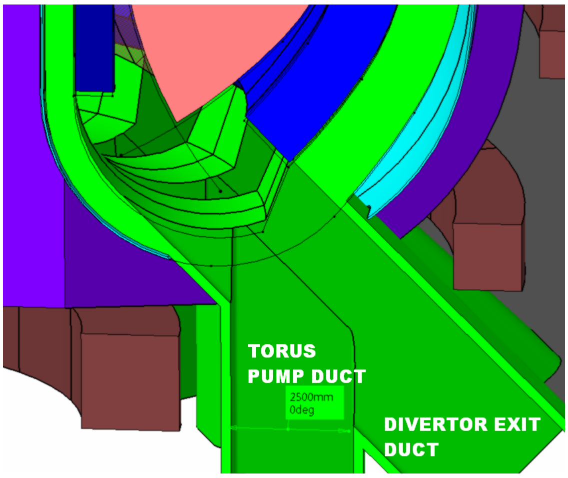

Figure 1 Vertical cross section of previous lower port configuration with vertical port for torus vacuum pump

3. Improved lower port configuration

The configuration of the lower port has been modified decreasing the initial inclination, including a kink at the level of the poloidal field coil to a horizontal duct and adding outer wall annexes for separate routing of the cooling pipes. The necessary modifications of the position of poloidal field coil #5 and the increased distance between divertor and torus vacuum pump have been evaluated. It was found that the benefit of the horizontal orientation predominates. All critical aspects mentioned in the previous chapter improve in the new configuration:

- Increased space for the torus vacuum pump.
- Larger opening cross section of the lower port towards the plasma chamber as the angle of the port converges towards horizontal direction, see Figure 5
- Space underneath the port available for the tokamak supporting structures pipe work inside the port is routed along the sides ,ceiling or floor not obstructing the pumping path
- Integration of magnet feeders below the machine possible

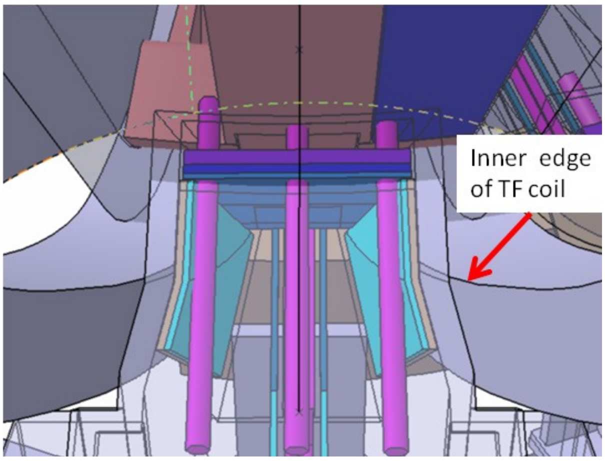

Figure 2 Radial view onto the lower port between two adjacent TF coils

The inclination of the lower port was reduced to zero to obtain a fully horizontal configuration. Therefore, as in ITER [3], a fully horizontal divertor maintenance scheme would be desirable also in DEMO. A horizontal extraction of the divertor would however require a significant reduction of the size of the breeding blanket and hence an impact on the tritium breeding ratio. As shown in Figure 3 the minimum inclination of the lower port is defined by the relative vertical position of inner and outer divertor targets and hence by the lower triangularity.
The toroidal size of the lower port is constrained by the inner edge of the TF coils and the lateral port walls are therefore tapered, see Figure 2. Within the inner contour of the TF coils toward the vacuum vessel (VV) there are conflicting requirements on the port walls: If the lateral port walls are parallel, this would allow for radial assembly of the complete lower port to the main VV as per ITER; however, this does not allow enough space to connect cooling pipes to the lateral divertors. A compromise solution that meets all requirements has not yet been agreed. Vertical assembly of the lower port is not possible due to the presence of the toroidal field coil inter-coil structure above the port.

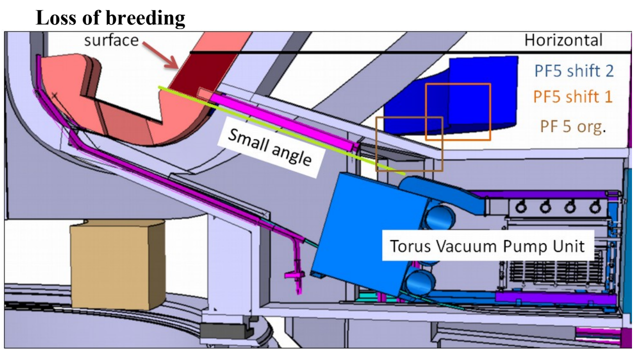

Figure 3 Vertical cross-section of the improved lower port configuration

Outer wall annexes were implemented in the lower port to route all in-vessel components feeding pipes to the ring manifolds in the lower pipe chase to avoid crossing the port cell to reach the ring manifolds. This is done to avoid

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the radiation hazards due to the N16-N17 generated in the cooling water as predicted for ITER [2], see Figure 4.

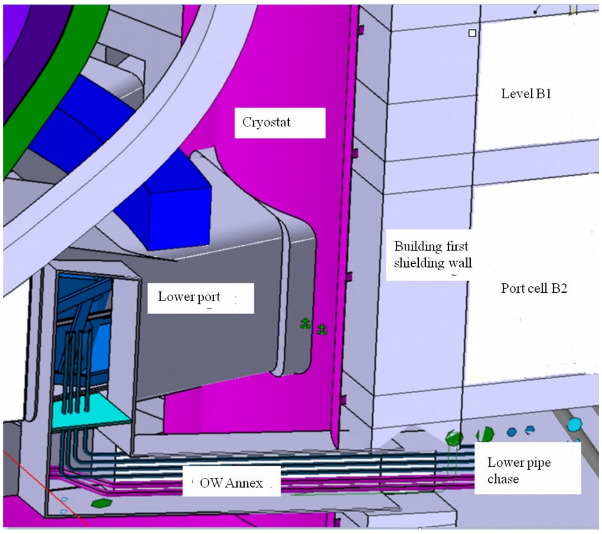

Figure 4 Cross section through building and outer wall annex of lower port showing the routing of the in-vessel components cooling pipes

4. Physical important interfaces

Lower port has physical interfaces to the following:

➢ Cryostat

The cryostat vacuum must be separated from the vacuum vessel vacuum. Rectangular bellows connect the two components that are able to compensate relative movements and to withstand relative pressure.

➢ Building

Both the level of the lower port and the lower port outer wall annex define the building floors levels, see **Figure 4.** The port cell must be at a suitable level for the lower port for the divertor remote handling tool to transport the divertor inside the port. The in-vessel components pipe work is routed in the outer wall annex, thereby defining the level for the lower pipe chase.

The machine support (of vacuum vessel & magnet coils) is implemented via the lower port onto the cryostat pedestal ring. The latter is fixed to a ring structure that is part of the building. At normal conditions only the machine's weight is supported by this ring structure. During seismic events this ring structure must support additional sideways forces.

➢ Vacuum vessel

The connection of the lower port to the vessel defines the opening in the vessel. The vertical top level of the opening is defined by the required back surface of the outboard blankets for the pipe connections of lithium lead. This has a knock on effect to the bottom support structure of the outboard blankets that are located above the upper port, see Figure 5

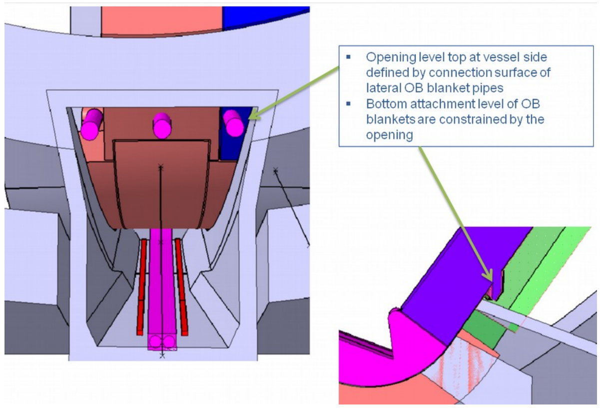

Figure 5 Radial view into the lower port onto the rear of the divertor cassettes and the outboard segments with indicated feeding pipes

5. Performed Assessments

5.1 Sensitivity analysis of locations of poloidal field coil 5 and poloidal field coil 6

As mentioned in the previous chapters the position of poloidal field coil 5 is one of the constraints for the vertical level of the lower port and had to be adjusted for the improved lower port configuration. The plasma equilibrium was adapted to shift locations of poloidal field coil 5 and poloidal field coil 6 considering as boundary condition a constant flux swings, [1]. Whereas it was possible to maintain the total number of MA·turns of poloidal field coil 5 in the shifted position, even a small downward shift of poloidal field coil 6 as low as 10cm would require an increase of its current by 2% which has a significant cost impact. It is therefore aimed at in the design of the lower port to minimise any downward shift of poloidal field coil 6. Shifting poloidal field coil 5 to provide vertical space to the lower port causes larger vertical forces the coil, see Table 1. These remain, however, within reasonable limits for the currently considered modifications. For comparison, the largest vertical force on any ITER poloidal field coil is 160 MN [4].

Table 1 Increase of vertical force on poloidal field 5 in poloidally shifted locations with respect to original location for adapted equilibria providing the original flux swing

Poloidal Field Coil (PF#)	**PF5-orig.**	**PF5-shifted1**	**PF5-shifted2**
Vertical shift	0	0.9 m	1.6 m
Max. vertical force	157.6 MN	150.9 MN	222.7 MN

5.2 Neutronic analysis

The neutronic analysis with the new design provided values on the two configurations of the horizontal lower port: (i) with the torus vacuum pump inside the port and (ii) an empty lower port. Moreover, 3D MCNP5 models

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considered a Water Cooled Lithium Lead blanket and neutron transport analyses. The nuclear heating in the superconducting coils and inside the port was quantified and determined. On top of that the effect of additional shielding blocks at the horizontal lower port entrance has been investigated as well as single and double wall port walls with different thicknesses. The shielding solutions provide sensible mitigation of nuclear loads in lower port area. Due to the inclination of the lower port and thickness of the main vacuum vessel body is locally reduced below the thickness of 600mm, typically considered as required minimum [7], [8]. The results revealed this as fundamental shielding issue on the bottom of the machine. An increase of the vacuum vessel thickness in the bottom area would at the same time require a vertical extension of the D-shape of the toroidal field coil and the consequent shift of poloidal field coil 6 away from the plasma. This was judged as undesirable, see section 5.1.

5.3 Monte Carlo simulation of the vacuum pumping port

An initial simulation for the pumping speed of the torus vacuum pump assembly located inside the lower port was performed. The results by test particle Monte Carlo simulations should give an indication what pumping path distance from the plasma to the metal foil pump surface has an acceptable pumping speed. Two possible surface positions inside the port were given where the cross section of the port area is big enough to host ether 6 or 12 metal foil pumps. As the distance between the two positions (Pos.2 &Pos.3 see Figure 6) was only 0.65m in comparison to 6m total length it appears that the effect in pumping speed difference is negligible. Position 1 was not taken into account because the of the limited cross section surface. The different metal foil pump configuration ether 6 or 12 pumps had a bigger effect. For detailed information on this topic please consult the paper of Thomas Giegerich. [9]

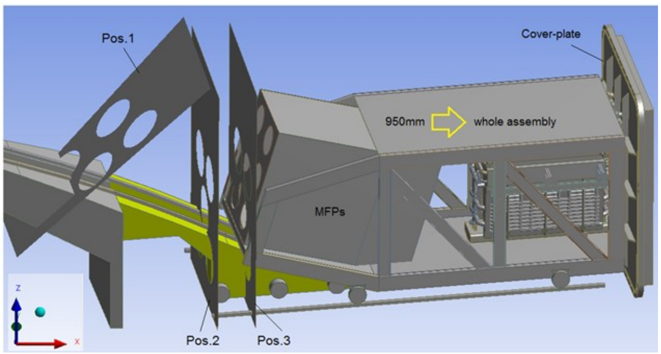

Figure 6 (TORUS PUMP POSITION)

6. Outlook

The author proposes an initial design of a horizontal lower port for the lithium lead option as it is the worst space wise. This layout has been evaluated on neutronic analysis and pumping speed calculation for the torus vacuum pumps. Based on the port design the values of the neutron heating of the TF coils were in some sections beyond the tolerable limits. Therefore, the author will first modify the design for the neutron shielding followed – again – by a thorough analysis. These modifications will be incorporated either by increasing the wall thickness, by permanent structures or removable shielding blocks. The modified design is going to be calculated to fit three constraints: 1) the pumping capacity for the torus vacuum pumping unit, 2) the gaps between divertor and blankets and finally, 3) the divertor opening.
In hindsight, the first design of the lower port has been too spacious. The author plans a second round of design optimisation where additional pipe work is taken into account such as the fore-lines for the vacuum pumps. To go even further two additional aspects will be included: The connection, disconnection and removal operation of the inner board blanket pipework which is running underneath the divertor and the supporting structure of the vacuum vessel and toroidal field coils on the pedestal ring.

7. Acknowledgments

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