Shielding concept and neutronic assessment of the DEMO lower remote handling and pumping ports

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A B S T R A C T

Within the EUROfusion Power Plant Physics and Technology Department the DEMOnstrational fusion power plant (DEMO) is being developed. One of the fundamental challenges is the integration of ports in the vacuum vessel. The lower port of the DEMO machine is particularly challenging due to tight space constraints imposed by the toroidal field (TF) coils and the requirement to provide a large open duct through both the divertor and inside the port to enable for vacuum pumping. In addition, feeding pipes of divertor and tritium breeding blanket need to be integrated and access space must be provided for various remote handling operations.

Several neutronics requirements need to be fulfilled, e.g. the nuclear heating of the superconducting TF coils and the gamma radiation levels inside the cryostat need to be limited to reduce occupational exposure to personnel during maintenance, and the irradiation damage and neutron heating in different components need to be considered in the design and limited. The results of neutronic analyses show that further shielding optimization is needed as maximum TF coil heating is still 5× the design limit and the SDDR values orders of magnitude above the target values inside the lower port duct. With this in mind the direction of future design developments is discussed.

1. Introduction

Neutronics simulations were performed in support of the development of the EU DEMO lower port. The shielding requirements in this port are especially difficult to meet due to the tight spatial constrains imposed by the TF coils and requirements for large openings in the divertor cassette to enable the flow of plasma exhaust particles through the lower port to the torus vacuum pumps.

To improve the shielding performance the design of the lower port went through several design iterations. Port walls were modified both in shape and thickness, and the divertor design evolved as well.

2. Neutronics analyses

2.1. Neutronics tools

Neutronics models were prepared through conversion of CAD models using SuperMC [1]. Neutron and gamma transport analyses of nuclear heating for TF coils were performed using MCNP5 v1.6 [2] and ADVANTG [3] was used to speed up these simulations. MCR2S [4] and MCNP6.2 [5] were used with variance reduction tool WWITER [6] in presented shut down dose rate (SDDR) analyses.

2.2. Nuclear heating of TF coils

Nuclear heating of the superconducting TF coils is typically one of the most limiting parameters when it comes to port integration. Getting all parts of the magnets below the relatively strict limit of 50 W/m^3 [7] is especially challenging in the case of ports where their functioning requires large openings, i.e. lower pumping port (LPP).

Pumping function for the LPP sets requirements for openings both in the divertor and in the port where the vacuum pumps are located. These openings can lead to values of nuclear heating in the coils significantly over the design limit and indeed the first LPP designs did not meet the

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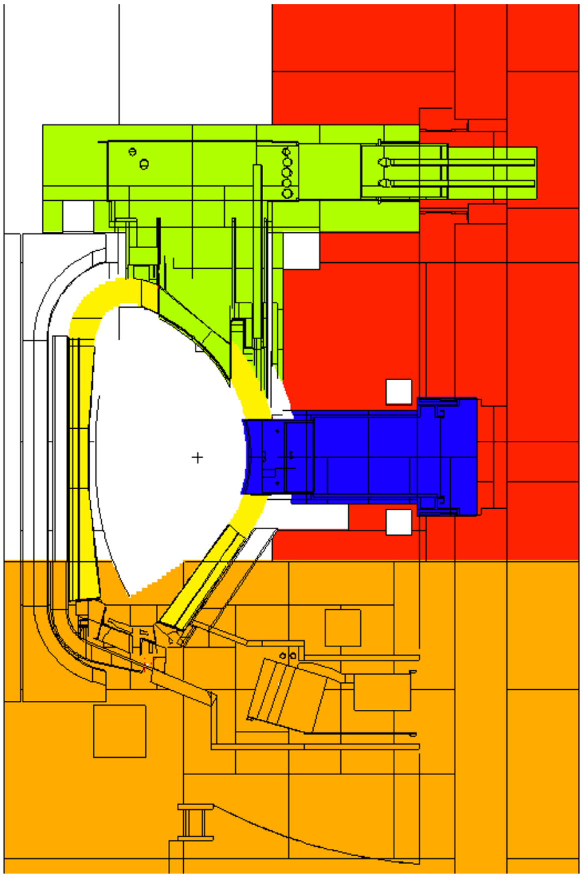

Fig. 1. Vertical cross-section of the MCNP model of DEMO showing the map of different MCNP universes. Color code is: basic DEMO structure – white, breeding blanket – yellow, LPP – orange, equatorial port – blue, upper port – green, and cryostat and bioshied – orange. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

requirements.

2.3. Shut down dose rate

The SDDR inside the cryostat was calculated for the case 12 days after plasma shutdown. This represents a typical planned interval between the reactor shutdown and maintenance work done in the areas of interest. SDDR analyses are important for estimation of where human access is possible and to optimize shielding in parts where human access is required. Important design targets for SDDR considered in this work are < 1000 μSv/h in port duct and < 100 μSv/h in port cell.

2.4. Geometry

All of the neutronics models used in this paper were single sector models based on the EU DEMO 2017 baseline. The baseline consists of 16 sectors (22.5° per sector), features an aspect ratio of 3.1, a major radius 8.938 m, minor radius of 2.883 m and fusion power of 1998 MW with an average neutron wall load of ~1 MW/m^2 and an irradiation lifetime of ~6 full power years (fpy).

Several iterations of the lower port were prepared. The pumping port (LPP) and remote handling port (RHP) have the same shape and share many of the features. However, while the RHP could in principle be to a significant degree filled with removable shielding components the LPP must remain sufficiently open to perform its vacuum pumping function. With this in mind the emphasis of the analyses was on the more challenging LPP as solutions could likely be implemented in the RHP as well.

Layered approximation of an HCPB tritium breeding blanket was used and studies of neutronic performance with WCLL are planned for the future.

2.5. Modelling strategy

MCNP's universes functionality was used to reduce time needed for geometry preparation and make the model that is as generally useful as possible. This way models of tritium breeding blanket, upper port, equatorial port and lower port can be changed without the need to convert other parts of the geometry. The cross-section of the MCNP model in where different colors are different universe is presented in Fig. 1. Such modelling enabled faster geometry changes, easier CAD to MCNP model conversions, and thus made faster geometry iteration possible.

2.6. Geometry iterations

Geometry of the LPP was changed multiple times to improve its shielding performance and different shielding options were considered. Geometry evolution is described in Table 1 and presented in Fig. 2.

3. Analyses and results

3.1. Nuclear heating of TF coils and geometry iterations

Maximum values of nuclear heating of the superconducting TF coils was and remains one of the challenging aspects of the LPP design. The vicinity of the magnets and requirements for large openings for vacuum pumping preclude various shielding strategies due to spatial constraints. Significant redesigns were required to reduce the nuclear heating in superconductors and while we were successful in reducing their maximum values further improvements are required. Results for the maximum values of nuclear heating in TF coils achieved with different models from Fig. 2 are presented in Table 2.

The opening in the divertor is responsible for a large amount of nuclear heating as it represents a direct pathway. Its effect was reduced in geometry iterations b), c) and d) through its reduced size and use of the shield above the divertor opening.

Single layered port wall (6 cm stainless steel) was identified as insufficient and was replaced with 20 cm thick walls of a mixture of stainless steel and water throughout iterations. A thick bottom wall was used in geometry iterations c) and d) to improve the shielding performance.

Additional shielding in the upper part of the lower port behind the divertor was tested in additional simulations with geometry c) and used as standard in iteration d). While it didn't significantly affect the maximum value of nuclear heating it did help to reduce the size of the hotspot in nuclear heating of TF coils.

Table 1
Brief description of geometry evolution.

Case	Changes implemented
a)	Initial model* [8]
b)	Horizontal port, shield above divertor opening, reduced size of the divertor opening.
c)	Thicker port walls, especially directly below the divertor, moved divertor opening.
d)	Divertor opening moved back to previous location, thicker shield above the divertor opening, thicker walls where possible, additional shield behind the divertor.

* This model used fully homogenized WCLL breeding blanket mix while all the rest featured layered HCPB.

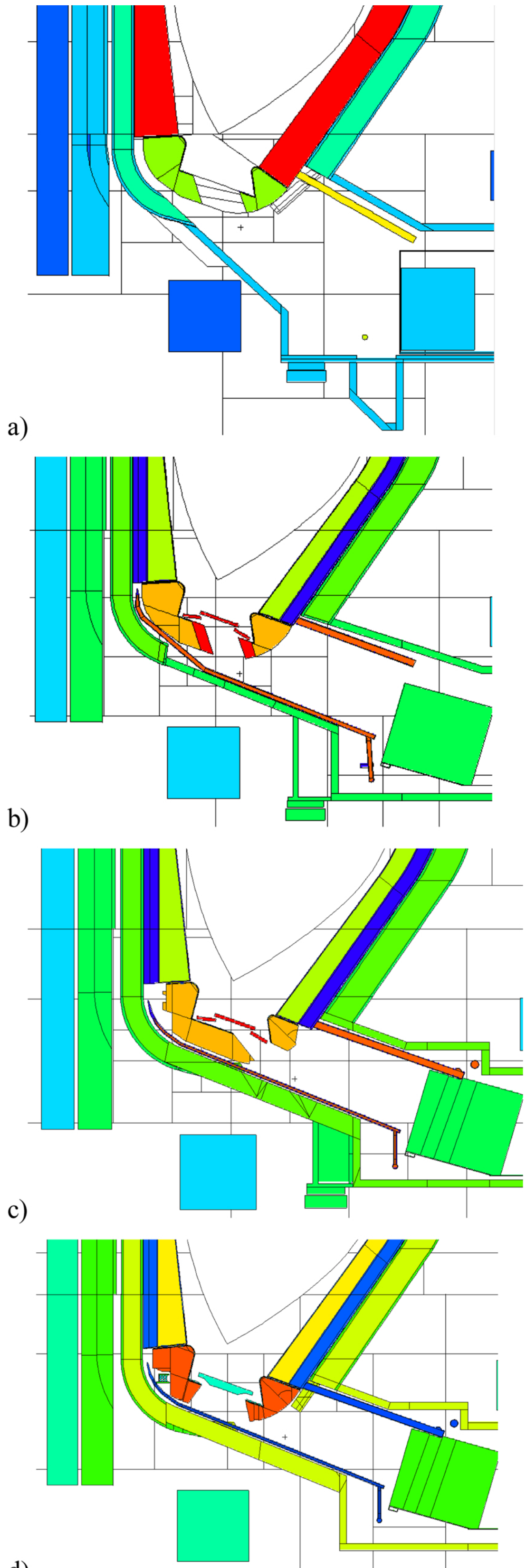

Fig. 2. Vertical cross-section different LPP configurations. Notable changes include different shapes of divertor opening, orientation of the port and thickness of port walls. Figures are in order of development where a) represents the initial port design and d) the latest. As the color in MCNP Visual editor is assigned for each MCNP input file individually the change in color in above geometries does not necessarily correspond with change in the material composition of visualized components.

Table 2
Maximum values of nuclear heating in TF coils.

Case	Max NH [W/m^3]
a)	3000-15000*
b)	6500
c)	1000
d)	250

* For different levels of additional shielding.

Further simulations were performed with the latest geometry configuration d) to assess the importance of different neutronic pathways and thus identify suitable new shielding strategies. Case 1: 2× density of the shield above the divertor (DS1) opening, case 2: shield behind the divertor (DS2) was removed, case 3: density of the wall on the LPP side walls was 2× higher to simulate the effect of thicker walls (WD), and case 4: implemented increased DS1 density and LPP side wall density at the same time. Results are presented in Fig. 3. And maximum values in Table 3 and show that a combination of additional shields is required to further decrease the maximum value of nuclear heating of the superconducting TF coils. For example, improved shielding in the divertor penetration region is effective for reduction of the hotspot directly below the divertor while the increased thickness of the port's walls reduces the hotspot near these walls but both these changes do not result in reduced maximum value of TF coil heating. A combination of both shielding enhancements was also tested and resulted in significant reduction of the maximum value of the TF coil heating. This can be explained by the presence of the two important neutron pathways indicated in Fig. 4. However, as the improvement of the shielding performance described above was tested through an increase in material densities a practically useful design solution corresponding to similar optical path need to be investigated.

3.2. SDDR analyses

SDDR analyses were performed on the case a) of the model and are currently being carried out for the case d) [9]. Dose rates to silicon and biological dose rates were estimated for different irradiation scenarios and different decay periods but of particular interest at this point are the results 12 days after shut down and for irradiation leading to 20 DPA of neutron damage to the first wall. It was found that due to openings in the divertor cassettes the lower port is a region of high dose rates. The values reached up to 479 Sv/h in the part close to the divertor, 608 mSv/h in port interspace near the vacuum pumps, and 72 μSv/h in port cell.

The improvements in the port design that lowered the TF coil heating also somewhat reduced the SDDR values in the lower port region. However, designs presented here were not yet optimized for SDDR and the improvements were mainly focused on reduction of the nuclear heating in magnets through neutron shielding strategies. There are still many shielding options that can reduce SDDRs in various parts of the lower port including gamma shields and current analyses will provide data on the best strategies to achieve this. Nonetheless, due to the experiences at ITER [10] and its functional requirements the design of the lower port is considered challenging.

3.3. Future work

As the shielding requirements were not yet met further optimizations and improvements to the shielding strategies are in progress. One of the possible strategies to further improve the shielding performance is to minimize the size of various openings. However, to ensure vacuum pumping capabilities of LPP are sufficient pumping system studies are required. Additionally, if RHP and LPP designs are to remain similar it needs to be ensured that divertor cassettes can be extracted through the

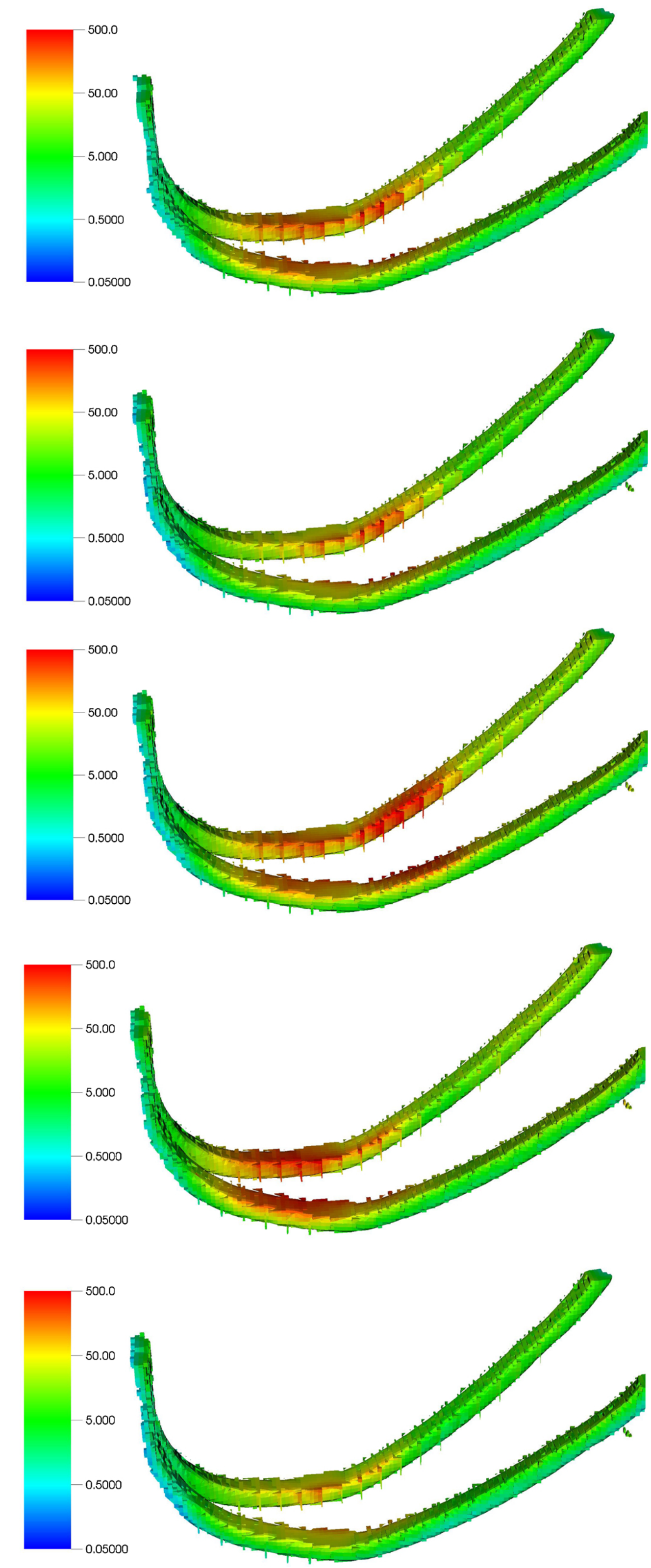

Fig. 3. Nuclear heating maps in W/m^3 in TF coils for different iterations of the latest geometry. From top to bottom: Original, 1, 2, 3, and 4.

RHP. Alternatively, LPP and RHP designs can diverge to better suit both functions.

SDDR analyses need to be performed for the most recent design to determine where the design must be improved. For further design optimizations both neutron and gamma shielding strategies need to be considered.

Table 3
Maximum values of nuclear heating in TF coils for different additional cases based on the latest geometry model (d).

Case	Geometry	Max NH [W/m^3]
Original	d)	250
1	d) + DS1	250*
2	d) - DS2	500
3	d) + WD	200*
4	d) + WD + DS1	150

* While the maximum is similar as for case d) the hotspot in nuclear heating is spatially significantly more limited.

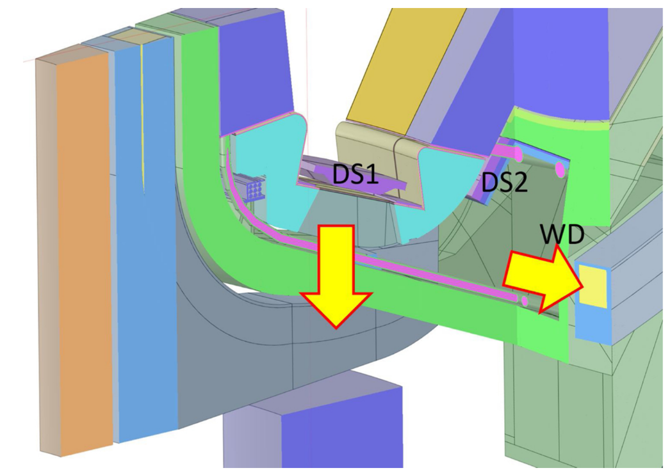

Fig. 4. Important neutron pathways that contribute to nuclear heating of TF coils.

4. Conclusion

Neutronics analyses were performed in support of the lower pumping and remote handling port development. Due to higher difficulty the main focus was on the pumping port where the need for openings that allow vacuum pumping make port design and integration especially challenging. Several iterations of the geometry were performed and shielding optimized.

While the strict requirements for the maximum value of nuclear heating are still not met the latest design reduced the values for about 60 × compared to the initial geometry. For the geometry with increased optical thickness of the shield above the divertor and side walls of the lower port the reduction was 100 × compared to the original model. However, further shielding optimization is required in order to meet the required limit for maximum value of nuclear heating ($< 50\ W/m^3$). This means that a significant design improvement is still needed and the results presented in this paper offer some guidance on the direction of design optimization.

Improvements to the design between the model already analyzed in terms of SDDRs and the latest available model in combination with other presented neutronics analyses give us some confidence that the new design will most likely perform significantly better in terms of SDDR. Additionally, SDDR-oriented shields can be implemented to further reduce dose rates strategic parts of the reactor, e.g. where human access is required.

CRediT authorship contribution statement

Aljaž Čufar: Visualization, Methodology, Investigation, Writing - original draft. **Christian Bachmann:** Conceptualization, Writing -

review & editing, Project administration, Supervision. **Tim Eade:** Investigation, Methodology, Writing - review & editing. **Davide Flammini:** Investigation, Methodology. **Curt Gliss:** Conceptualization, Methodology, Resources, Writing - review & editing, Project administration. **Ivan A. Kodeli:** Supervision. **Domenico Marzullo:** Resources. **Giuseppe Mazzone:** Resources. **Christian Vorpahl:** Conceptualization. **Andrew Wilde:** Resources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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