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Neutronics analyses for EU-DEMO 2023 electron cyclotron port

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ABSTRACT

One of the fundamental challenges in the development of a fusion power plant is to integrate all the systems required for the operation of the power plant into a machine that fulfills all the design requirements. This includes designing sufficient shielding against neutrons and gamma rays to ensure that the machine can operate reliably throughout its planned lifetime.

The electron cyclotron (EC) heating is one of the systems critical to heating and controlling the fusion plasma. In the EU-DEMO reactor, the EC system is integrated into an equatorial port. However, the challenge with this system is that the waveguides required for it to function act as neutron and gamma ray streaming paths, which makes controlling the nuclear loads inside and behind the EC port a challenge. This concerns both the components of the EC system itself and components and systems outside the equatorial port where the EC system is located, e.g. the superconducting toroidal field coils.

The latest iteration of the EU-DEMO EC heating system from 2023 was analyzed. The main nuclear loads have been calculated and the shielding performance optimized to ensure that the design limits are met. These analyses include calculations of nuclear heating in EC port, determination of peak nuclear heating in the toroidal field coils and peak neutron-induced damage (DPA) in the components exposed to the plasma neutrons.

1. Introduction

The design and integration of various systems is a crucial part of the development of a feasible concept for the EU-DEMO (European demonstration) fusion power plant. When integrating a system such as the electron cyclotron (EC) heating into the equatorial port, the effects on the surrounding systems are checked, e.g. nuclear heating (NH) in the superconducting toroidal field coils (TFCs), and the nuclear loads in the most exposed components of the system are quantified, e.g. nuclear heating and neutron-induced damage in the form of DPA (Displacements Per Atom).

In this paper we describe the analyzes and optimizations of the shielding performed for the EU-DEMO 2023 EC system design, which was developed based on the results of previous design iterations such as [1,2].

2. Nuclear analyses

2.1. Tools used

The tools used for the neutronics analyzes were MCNP5 v1.6-based [3] ORLN-TN [4] for neutron and gamma ray transport together with neutron data from JEFF 3.3 [5] and gamma-ray data from MCPLIB84 [6] and ADVANTG [7] to improve the computational efficiency of these simulations.

The geometry models used in the simulations were converted from CAD to MCNP geometry using SuperMC [8] and GEOUNED [9]. A spatial mesh of 5 cm × 5 cm × 5 cm was used for the nuclear heating and DPA analyzes.

3. Geometrical model

The geometric model was based on a single sector model (22.5°) for the 2017 EU-DEMO baseline and the MCNP model is shown in Fig. 1. The EC port model was inserted into the MCNP model by using the universe functionality in MCNP and the model of this EC port is shown in Fig. 2. To improve shielding the walls of the EC port are thicker close to the reactor while further away they are thinner (Fig. 3). When discussing thickness of the port walls in this paper, only the thick part of the port walls is considered and its material is defined as homogenized mix of 80% SS316LN and 20% water. Both fixed mirror (FM) and steering mirror (SM) modules are modeled as a homogenized mix of

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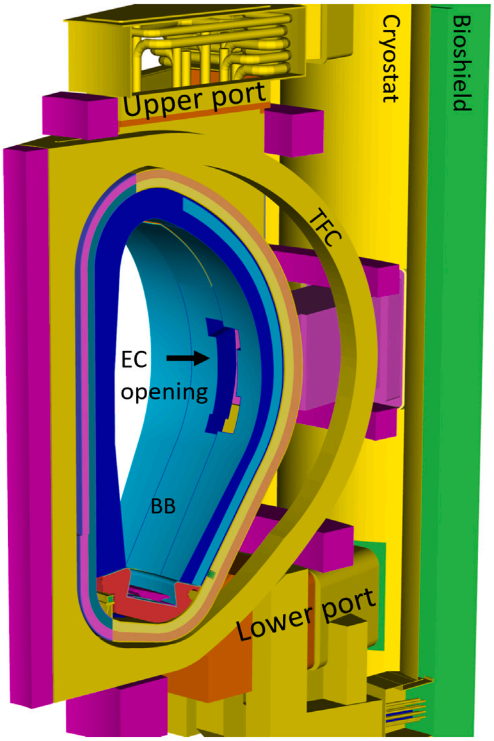

Fig. 1. MCNP model used in the analyses.

80% SS316LN and 20% water while the shield behind the FM module (seen in Fig. 3) is modeled as a homogenized mix of 60% SS316LN and 40% water. Similarly TFCs are modeled as made of two layers - TFC steel casing and magnets where a homogeneous mix of magnet and insulator materials is used. Reflective boundary conditions are used at the edges of the sector.

Simplifications used in the model, such as the homogenization of materials and reflective boundary conditions, influence the results, especially the peak values. The introduced biases can go in both directions. Simplifications in the material and geometry description likely mean that our peak values are lower than in more realistic models, while reflective boundary conditions mean that the nuclear loads on the side where the EC port is closer to the reflective boundary are higher than they would be in a 360°model. Our rationale for these simplifications is that at this stage of the system design and integration process, biases introduced by such simplifications are acceptable, as different levels of design maturity for different systems would mean that including different neighboring systems would significantly increase the number of assumptions made and complicate the modeling process, while the overall uncertainty would likely not be decreased. At this point, the strategy is to ensure that the design limits are met with a sufficient safety factor (e.g. factor of 2 or more) for each of the systems filled into their own reactor sector. If this is the case for all reactor systems, then integrating them together should not lead to a particularly problematic reactor design. Similarly, components approximated by homogenized material mixtures are justified by the fact that often detailed designs are not yet available as in these analyses we are estimating the approximate amount of shielding material needed before these shields are designed. This is another reason why design limits need to be met with significant margin or at least a realistic way to improve shielding performance must be found to ensure that the designs are feasible.

3.1. Nuclear heating in toroidal field coils

One of the commonly limiting factors in the integration of DEMO systems is the peak local nuclear heating in the superconducting

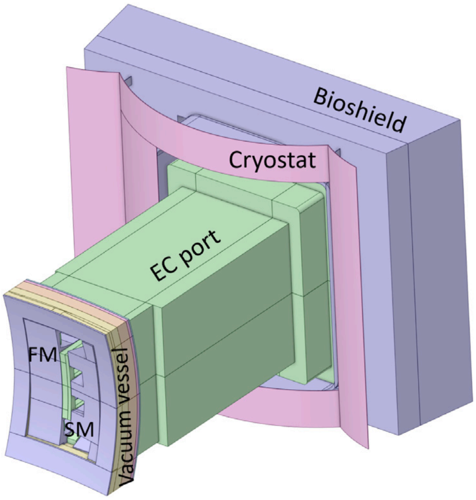

Fig. 2. Geometry of the EC port.

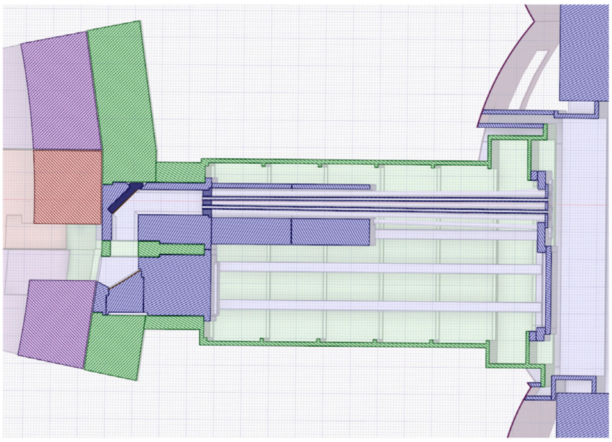

Fig. 3. Cross-section view through EC port geometry to show one of the pathways where dogleg-like geometry with waveguides and mirrors is used to reduce direct streaming pathways for neutrons and gamma rays.

TFCs. The limit for peak local nuclear heating in these magnets is 50 W/m^3 [10]. Since the waveguides for the EC system require openings of considerable size, neutron and gamma ray streaming can be an issue and it can be a challenge to provide sufficient shielding. In the present design, this is partially mitigated by the use of mirrors which make the shape of the openings in a dogleg/labyrinth-like (see Fig. 3) and ensure that there are no direct lines of sight through the EC system.

The analyzes revealed shortcomings and several cases were tested to address them. The shielding material used in this work is a simple homogeneous mix of 80% SS316LN and 20% water. The cases analyzed in this paper are:

0. Original design with three of the four port walls with a thickness of 20 cm and the wall on the FM side 30 cm.
1. Design where the thinner port walls have been made thicker (Fig. 4) so that all four walls are 30 cm thick and there is a 30 cm thick shielding block behind the SM module (Fig. 5).
2. Design where all 4 port walls are 30 cm thick but the material density has been increased to simulate 45 cm thick walls. Behind the SM module is a 30 cm thick shielding block.
3. Like case 2, but the thickness of the shielding block behind the SM module has also been optically increased to 45 cm by increasing its material density.

Table 1
Peak values of local nuclear heating (NH) in toroidal field coils. Statistical uncertainties of results in peak nuclear heating area is generally below 10% for both neutron and gamma ray component on the FM side and cases number 0 and 1 on the SM side while the statistical uncertainty of the gamma ray heating for the best shielded cases can reach 14%.

Num.	Case	Peak NH in TFCs - FM side [W/m^3]	Peak NH in TFCs - SM side [W/m^3]
0	Original	35	100
1	30 cm wall, 30 cm shield	30	30
2	45 cm wall, 30 cm shield	20	15
3	45 cm wall, 45 cm shield	20	15

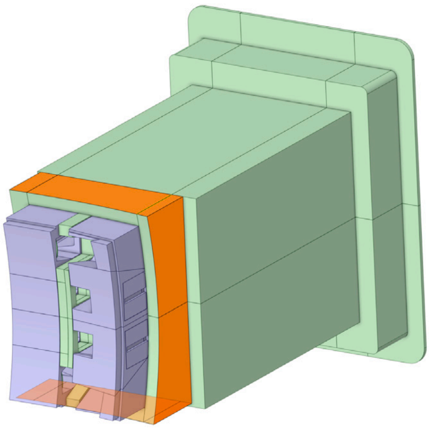

Fig. 4. Lateral walls (marked in orange) with original thickness of 20 cm increased to 30 cm for cases with improved shielding.

The nuclear heating, i.e. the heating due to the neutrons from the plasma and the gamma rays produced by interaction of these neutrons with materials, in the TFCs was calculated, see Fig. 6 for the example of case 0, and the peak local values for different cases were determined, see Table 1. The results of these analyzes show that the TFC coil on one side of the EC port is not sufficiently protected. With this in mind, we tested different strategies to improve the shielding. It was found that two improvements are required to improve the shielding performance:

- The thickness of the port walls must be over 20 cm which was the default thickness for 3 out of 4 port walls. Based on analysis, the recommended thickness is at least 30 cm on all 4 walls.
- The steering mirror plug needs to be thicker or additional shielding must be placed behind it. 30 cm thick block of additional shielding material seems sufficient.

The analyzes and suggested changes inform the future design of the EC system and the EQ port and will be taken into account in the next iteration of the design. If necessary, further optimization can be carried out by optimizing the material composition and the size of the shielding structures.

These values should also be considered in the context of other previous work on the EC system in a large tokamak, i.e. ITER's EC launcher [11,12]. Peak values for NH in TFCs in the EC launcher region in ITER were found to be between 200 W/m^3 and 300 W/m^3. However, here it needs to be stressed that the design limit for peak NH in ITER's TFCs is 1000 W/m^3 while for DEMO it is set to 50 W/m^3.

3.2. Nuclear heating and DPA in EC port components

Nuclear heating of EC port components is shown in Figs. 7 and 8 and defines their cooling requirements, while neutron-induced damage in the form of DPA, shown in Fig. 10, informs the material selection for the component as well as defines the component lifetime and its maintenance requirements. The peak DPA values were found to be $3.1\,DPA/FPY$ and $3.4\,DPA/FPY$ in the SM and FM modules respectively. The additional shielding placed behind and around the EC port plug tested in the previous subsection has no effect on the peak DPA loads in most exposed parts of the EC port, therefore these results are relevant for all cases discussed. The ratio between nuclear heating maps shown in Figs. 7 and 8 on the other hand, is shown in Fig. 9 and clearly demonstrates how additional shielding reduces the nuclear loads in and around the EC port.

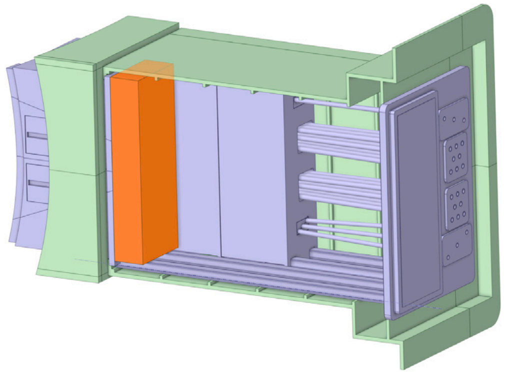

Fig. 5. Additional shield behind the SM module. One of the port side walls is hidden to show the insides of the port.

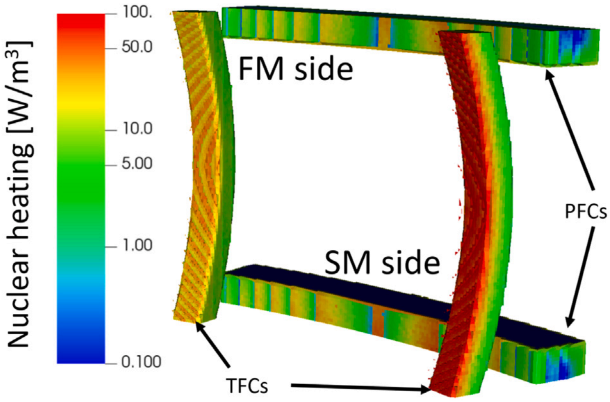

Fig. 6. Nuclear heating in superconducting magnets near EC port, i.e. Toroidal Field Coils (TFCs) and Poloidal Field Coils (PFCs), in W/m^3 for case 0.

Peak values of DPA in EC port modules show that to some extent the idea of having a SM module take the majority of the peak nuclear damage and having FM module more protected and thus extending its operational life was not realized. Similarly, the part of the vacuum vessel next to the top and bottom part of the module is also exposed to

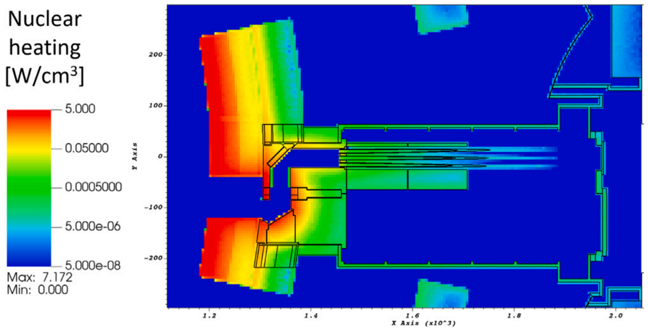

Fig. 7. Nuclear heating for case 0 in W/cm^3, XY view through steering mirror opening (Z = 26.8 cm).

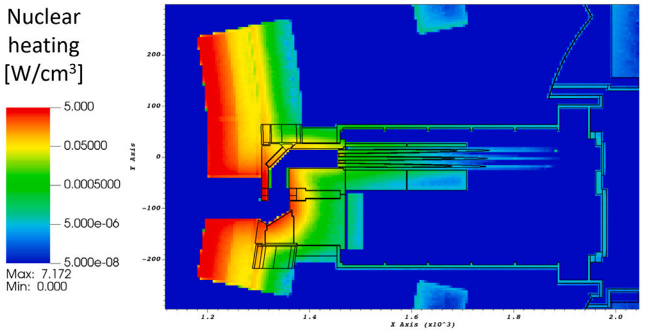

Fig. 8. Nuclear heating for case 2 in W/cm^3, XY view through steering mirror opening (Z = 26.8 cm).

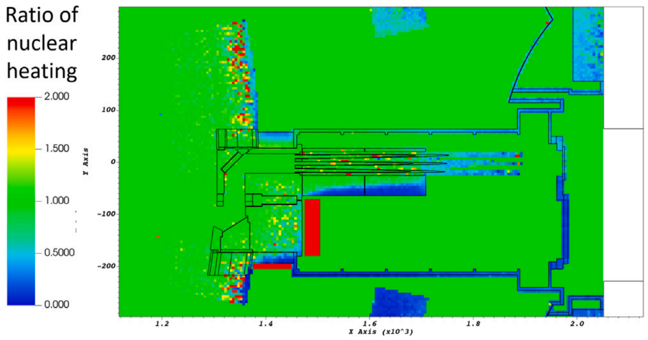

Fig. 9. Ratio of nuclear heating for the case 2 and case 0 (NH(case 2)/NH(case 0)), XY view through steering mirror opening (Z = 26.8 cm). Larger red squares show locations where additional shield was added (ratio there is very large, in principle infinite as void was replaced by material) and the effect of these shields on the nuclear heating inside and outside the port is visible. Statistical uncertainties for neutron and gamma ray heating in thin components of the port are generally well below 10% but can be significantly higher in thick shields or directly behind them (as visibly by the statistical noise in those regions).

excessive DPA values (up to 3.9 DPA/FPY in the part just below the EC modules, significantly above the lifetime limit of 2.75 DPA [10]). The origin of these excessive DPA loads is the shape of the opening in the tritium breeding blanket which is such that the top part of the FM module is significantly exposed and at that point reaches values even higher than the values in the SM module. Furthermore, the part of the vacuum vessel above the top part of the FM module and the bottom part of the SM module together with nearby part of the vacuum vessel are also exposed. However, as the shape of the opening is dependent on the function of the EC system, i.e. which parts of the plasma can the system reach, and has limitations from the point of view of the breeding blanket construction, this is not a simple modification.

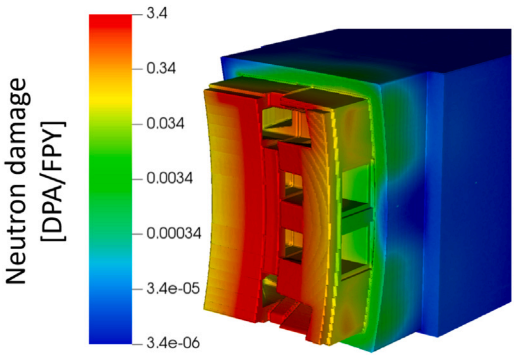

Fig. 10. Neutron induced damage in terms of DPA in SM and FM modules. Most exposed parts have a statistical uncertainty below 0.5%, whole front part below 2% and most of what is visible on the plot below 5%.

4. Conclusions

A 2023 design of the EU-DEMO EC system was integrated into a neutronics model and its main neutronics characteristics were tested. Since the design was based on earlier designs, it performed relatively well, except for some minor issues, namely that the peak nuclear heating in the TFCs was found to be too high on one side and the peak DPA in the FM module and vacuum vessel were actually higher than in the SM module, contrary to the design's intention. A possible solution to the first problem was found by increasing the thickness of the port walls and adding shielding behind the SM module. Alternatively, it is possible that these shielding improvements could also be achieved by optimizing the shielding materials, e.g. by optimizing the water-steel mix, or using more advanced shielding materials like tungsten based shields. However, the second problem requires more effort, e.g. increasing the size of the SM module at the expense of the FM modules to ensure that the peak nuclear loads occur in the SM module, or changing the shape of the opening in the tritium breeding blanket to better protect the FM module and vacuum vessel.

CRediT authorship contribution statement

Aljaž Čufar: Writing – original draft, Investigation, Data curation. **Bor Kos:** Writing – review & editing, Data curation. **Dieter Leichtle:** Writing – review & editing, Supervision. **Peter Spaeh:** Writing – review & editing, Data curation.

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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Data availability

The data used is in a form of freely accessible nuclear data and in a form of models/geometrical data which can easily be shared within EUROfusion. Outside users need agreement with the consortium.

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