Nuclear Science and Technology Symposium - SYP2022
Helsinki, Finland, 1-2 November 2022

Serpent2 neutronics calculations for a HELIAS fusion reactor

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ABSTRACT

This contribution presents the fusion neutronics studies carried out for HELIAS reactor design using Monte Carlo neutron transport code Serpent2. The paper shows how complex geometries can be directly imported from CAD to Serpent2 using STL files. This allows, for the first time, to include the full non-planar field coils in the HELIAS neutronics simulations. Nonetheless, a simplified total geometry using six layers (and the field coils) is used to calculate the tritium breeding ratio and neutron flux at critical components of the design. In more detail, the tritium breeding is calculated in the breeding blanket responsible to a self-sufficient tritium cycle and the neutron flux is volume integrated inside the non-planar field coils posing a critical limit for neutron flux. It is found that enough tritium is being bred in the given geometry, while further protection of the field coils is needed to shield the neutron flux to acceptable limits. The key result of this paper is not the actual numbers, that will change when the geometry will be modified, but rather the proof-of-principle that Serpent2 can be used to account for the very complex geometry of stellarators to model fusion neutronics.

1 INTRODUCTION

Thermonuclear fusion appears as one of the possible solutions to fight against the climate change. The basic principle is to fuse two light hydrogen isotopes deuterium (D) and tritium (T) into heavier alpha particle and a neutron, releasing 17.6 MeV of energy – 3.5 MeV carried by the alpha and 14.1 MeV by the neutron. This DT fusion is being currently researched not only by national and international publicly funded research institutes, including the ITER project [1] but also by growing number of privately funded companies aiming to commercialize thermonuclear fusion reactors in the future.

To produce fusion, the fusion fuel needs to be confined. For DT fusion to occur, the fuel needs to be heated up to past million degrees. Therefore, fusion fuel is in the form of a plasma. A natural way to confine plasma is by using magnetic fields, created by field coils and induced field caused by the conductively driven plasma current. Toroidal shape is the preferred options, since in this way the geometry forms a magnetic geometry with no leaking ends. A tokamak [2] is the most advanced design. However, due to the induced plasma current, is is both limited to pulsed operation and has several instabilities that make the operation challenging. An alternative solution, with no plasma current and the total field only created by using field coils, is the stellarator [3].

This paper shows calculations of the Monte Carlo neutron transport code Serpent2 on the HELIAS stellarator geometry. The fusion community has long trusted on MCNP calculations related to fusion neutronics (see e.g. [4]), but recently Serpent2 work has been active as well. The stellarator geometry calls for advanced geometry handling, which is the clear benefit of Serpent2 compared to MCNP5 – as Serpent2 can work with the STL format that can be exported directly from most CAD softwares. This Serpent2 feature exceeds the standard geometry construction methods using the constructive solid geometry. Further description of the Serpent2 code can be found from [5] and references therein. After this introduction, the HELIAS reactor is introduced in the Chapter 2 together with the Serpent geometry for it. Numerical results related to tritium breeding ratio (TBR) and neutron flux at the helical field coils are shown in chapter 3. The work is concluded in Chapter 4.

2 HELIAS REACTOR AND SERPENT2 GEOMETRY

The HELIAS reactor is a stellarator with 5-fold toroidal symmetry and a 22m major radius. The design has been proposed by the Max-Planck Institute for Plasma Physics (IPP) already around decade ago [6]. The design is with 3000 MW fusion power and with 1000MW net electric output [7]. For neutronics studies, the geometry needs to be reduced. This is mainly because detailed components of the reactor are currently not available and the design itself is in an early stage. The current neutron model consists of 6 layers, including three layers of vacuum vessel, plasma, and the breeding blanket, as shown in Figure 1.

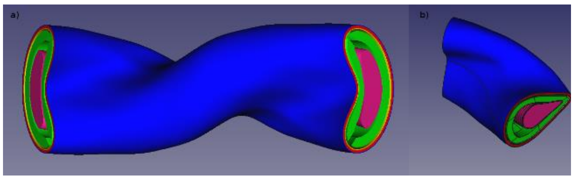

Figure 1. Left: A full module of the HELIAS geometry which represents 72-degree sector in the full 360-degree geometry. The full module is represented as a converted mesh in FreeCAD. Right: An original half module model in STP format which is converted to the STL format and the counterpart for the full module is created by rotations/translations. Geometries consist of 6 layers from outside to inside: vacuum vessel - outer shell (blue), vacuum vessel - shield (red), vacuum vessel - inner shell (yellow), breeding blanket (green), LCFS (last closed flux surface) and plasma (deep pink).

The breeding blanket is one of the most essential components of any fusion reactor. It has several vital roles in realization of fusion power. As the name suggest, the first and most important task is to breed tritium using the nuclear reactions with neutrons and lithium isotopes 6 and 7. As important is the role as a radiation protection for the superconducting field coils located outside the blanket. Moreover, the blanket can act as a coolant and possibly also as a moderator for the fast fusion neutrons. Due to its complex role, alternative technological and material solutions have been introduced, including at the very least Helium-cooled lithium-Lead (HCLL) [8], water-cooled lithium-lead (WCLL) [9] and Helium-cooled pebble-bed (HCBB) [10] concepts. In this work, a dual coolant lithium-lead (DCLL) concept is examined for HELIS design. The actual geometry of the breeding blanket is adopted from the European DEMO tokamak design [11] and the dual-coolant comes from helium being coolant not only for the first wall but also for the stiffening grid, while lithium-lead act as a coolant for the breeder zone inside the blanket. The model utilized in this work includes the breeding blanket (BB) and the back supporting structure (BSS). Each of these blanket concepts have their advantages and disadvantages and are all being currently studied in parallel. The choice of the concept will need to be done in the future but falls far beyond the aim of this paper.

Since the HELIAS has a 5-fold symmetry, the geometry includes 72-degree sector/module that will be periodically repeated five times to form the full 360-degree stellarator geometry. Moreover, a single 72-degree module is formed from two identical half-modules that are attached to each other using rotations and translations, as shown in Figure 2. All these operations can be done inside Serpent2, giving geometry input only for the 36-degree half-module. Serpent2 allows user to choose from two identical methods to generate the full model: 1) the geometry is generated using user-defined symmetry and rotations+translations and neutrons are free to move in the full 360-degree system or 2) reduced symmetry is used and neutrons are reflected/translated from the boundaries of the reduced geometry. We have noted that the earlier work [12] carried out by MCNP5 utilized reflective boundary conditions on the half-module geometry. This geometry results in wrong geometry since only reflection is not enough to complete a correct full module, but a 180-degree roll is needed as shown in figure 2. Nonetheless, we wanted to simulate the reflective geometry with Serpent2 as well to see how big of a difference this will produce in the tritium production.

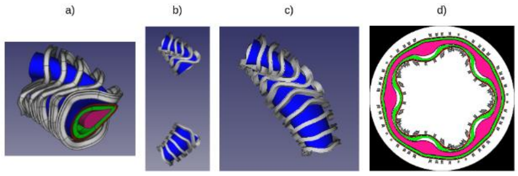

Figure 2: a) The original half module including the non-planar field coils in STP format. b) The original half module (top) and its counterpart (bottom). The counterpart is a mirror of the original part which is also rolled by 180 degrees. c) The connected full module by 72-degree rotation around the z-axis. d) The full geometry plotted in Serpent2 where the universe symmetry method is applied.

The last piece of building the neutronics geometry include the material compositions, nuclear libraries, and the neutron source. In this work, we present two different material compositions for the breeding blanket, both are adopting a homogenous material composition inside the BB. These are dubbed M24 and M41. While in M41 BB and BSS components are homogenized in the whole blanket volume, in M24 only the BB components are homogenized in whole blanket volume resulting in higher lithium-lead fraction. The material compositions are given in table 1.

Table 1. Material compositions of M41 and M24, the density is 8.317 g/cm^3 and 8.7319 g/cm^3 for M41 and M24, respectively.

Variant	Component	Volume fraction (%)
M41	LiPb	52.49
M41	He	5.48
M41	Al_2O_3	0.09
M41	W	0.26
M41	EUROFER	41.70
M24	LiPb	70.47
M24	He	4.39
M24	Al_2O_3	0.16
M24	W	0.47
M24	EUROFER	24.50

For the nuclear reactions, several different libraries are used to see the effect of varying cross-sections on the calculated quantity (here, tritium breeding ratio). A neutron source is adopted from [13].

3 RESULTS

3.1 Tritium breeding ratio

As mentioned, DT fusion operates with deuterium and tritium as a fuel. While deuterium is abundant in sea water, tritium is a radioactive isotope with half-life of 12.32 years. The strategy to produce tritium relies on breeding it inside the fusion reactor. This can be done using breeding reactions between neutron and lithium 6 and 7, which are both found in natural lithium. Unfortunately, lithium 6 has both higher capture cross-section, especially at low neutron energies, and much lower natural abundancy (7.59%). This means, the breeding blanket material needs to be enriched with lithium 6.

The main goal of the breeding blanket is to breed enough tritium to be used as a fuel. A relation between the tritium production rate (TPR) and the neutron source rate is called the tritium breeding ratio (TBR): TBR=TPR/source rate. To account for the losses and other uncertainties in modeling, a minimal TBR of 1.15 in Monte Carlo simulations is often utilized a figure of merit [14].

Table 2 summarizes the results of TBR calculations carried out with different material compositions, nuclear libraries, and different model accounting for the geometry production.

Table 2 Summary of TBR calculations using Serpent2 with multiple material compositions, nuclear libraries, and the geometry models

Material composition	Nuclear library	Geometry model	TBR
M41	JEFF311u	full	1.162
M41	JEFF33	full	1.167
M24	JEFF311u	full	1.34
M24	JEFF33	full	1.34
M24	JEFF33	reflective	1.307

We note that the Serpent2 results are found to agree with the MCNP5 calculations within around 5% accuracy. This discrepancy is currently under further research. As of currently understood, the reflective geometry utilized by MCNP5 seems to not explain the difference as such. More importantly, we note that using the wrong reflective boundary condition seems to result in lower TBR compared to the calculation with the correct 360-degree model. The correct geometry is therefore needed for further HELIAS neutronics studies to produce accurate results for TBR.

3.2 Neutron flux at the field coils

One of the most vulnerable components in the HELIAS design are the helical field coils. In the given geometry, they must be located relatively near to the plasma. Thus, being irradiated by neutrons. Therefore, a major design driver for such geometry is to assess the neutron flux at the coils. This can be done with Serpent2, which allows a full implementation of the helical field coils. The coils are divided to jacket case and winding packs. In this work, we show integrated neutron fluxes over the winding pack region, that is the most vulnerable part of the coils. Similar work was carried out by MCNP5, although a significantly reduced geometry was utilized [12]. Therefore, this work is not directly comparable to the earlier work. The flux is divided to slow (E<0.1 MeV) and fast (E>0.1 MeV) component and the results are shown in table 3.

Table 3. Integrated neutron flux (in units of $1x10^{18}/cm^2y$) results with material composition M41. Fast and slow neutron fluxes are calculated together with total flux. The time unit of neutron flux is per year. Neutron flux limits: fast neutron flux (E > 0.1 MeV) to the Nb3Sn superconductor ≤ $1x10^{18}$ n/cm2, integral neutron flux to the epoxy insulator ≤ $1x10^{18}$ n/cm2. The values exceeding the limits are colored

in red. There is an operational time limit of 6FPY (Full Power Year) for HELIAS [12] where the results must be multiplied by 6. The values below the initial limit but above the operational are colored in orange. Simulation consisted of 2×10^8 particles and 100 batches. OP: original part, CP: counterpart.

Layer	slow flux	fast flux	total flux
OP coil 1	1.12±0.02	0.90±0.01	2.01±0.03
CP coil 1	1.05±0.02	0.85±0.01	1.90±0.03
OP coil 2	1.10±0.02	0.58±0.01	1.68±0.03
CP coil 2	0.87±0.02	0.47±0.01	1.34±0.02
OP coil 3	3.20±0.03	1.91±0.02	5.10±0.04
CP coil 3	0.73±0.01	0.39±0.01	1.12±0.02
OP coil 4	0.39±0.01	0.17±0.001	0.56±0.01
CP coil 4	0.12±0.005	0.05±0.003	0.18±0.007
OP coil 5	0.12±0.006	0.05±0.002	0.17±0.07
CP coil 5	0.11±0.005	0.04±0.002	0.15±0.007

As can be noted from above table, most of the coils exceed either original or both the original and operational neutron flux limits. Therefore, a further optimization of the coil and breeding blanket must be carried out. As the design of the HELIAS reactor is still in its initial stage, such results are not worrisome but important to guide the next steps towards a feasible reactor design. The reader must also bear in mind that these calculations are carried out under several simplifying approximations, e.g. homogenized breeding blanket material composition and simplified total geometry. As such, these results can only be considered as initial and guiding rather than final proof-of-principle results. Most importantly, these results show that Serpent2 can model the full geometry of complex field coils in stellarator reactor. As such, it is an important outcome of this paper.

4 CONCLUSIONS

This paper presents simulations of neutron transport in HELIAS reactor geometry using Serpent2 Monte Carlo code. The geometry utilized includes a complex set of non-planar field coils, six layers including vacuum vessel, breeding blanket, and the plasma. The results show that 1) a necessary tritium can be bred in the breeding blanket with the given geometry, 2) some of the non-planar field coils are irradiated with too large neutron flux and need further protection in the next design iteration, and 3) Serpent2 can incorporate very complex geometries to model neutronics in HELIAS fusion reactor. Next, the results shown here will be benchmarked against the MCNP5 calculations.

ACKNOWLEDGEMENTS

This work was partially funded by the Academy of Finland project No. 324759 and No. 328874. This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom Research Training Programme of the European Atomic Energy Community for the period 2021-2025 complementing Horizon Europe. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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