EUROfusion

WPS2-CPR(18) 19908

A Huler et al.

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Preprint of Paper to be submitted for publication in Proceeding of 49th Annual Meeting on Nuclear Technology (AMNT 2018)

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Use of the Cell Based Importance Sampling Technique in Neutronics Shielding Calculations of a Simplified Stellarator Model

André Häußler[1], **Ulrich Fischer**[1]

[1]Karlsruhe Institute of Technology (KIT), Institute for Neutron Physics and Reactor Technology (INR)

1. Introduction

The Helical-Axis Advanced Stellarator (HELIAS) is a conceptual design of a fusion power reactor proposed by the Max Planck Institute for Plasma Physics (IPP) in Greifswald, Germany. HELIAS-5B is a specific 5-field-period concept using the Deuterium-Tritium fusion reaction with a fusion power of 3000 MW [1]. A thorough neutronic design analysis has to be performed for this stellarator in order to provide the input required for the reactor design.
A stellarator confines the hot plasma with external magnetic fields only produced by non-planar shaped modular field coils. The use of specific non-planar shaped modular field coils is necessary to generate the rotational transform of the magnetic field in the plasma chamber. This type of fusion reactor represents a challenging task for the design and maintenance of technological components such as the breeder blanket and the radiation shield as outlined in figure 1.

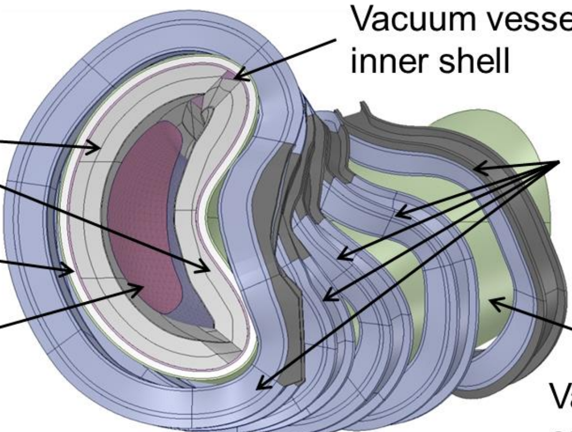

Figure 1: HELIAS-5B CAD model including material layers and last closed flux surface [2].

The standard approach to develop geometry models for neutronics design analysis is to use computer-aided design (CAD). The developed models are usually not directly applicable for Monte Carlo (MC) particle transport codes and need preprocessing with regard to the geometrical simplification and adaption to the requirements of neutronic simulations including the decomposition of complex CAD models [3]. One suitable way

to process the CAD model of HELIAS is the application of the Direct Accelerated Geometry Monte Carlo (DAGMC) method. The DAGMC code is an extension to the Monte Carlo N Particle (MCNP) transport code, which allows using complex surface descriptions, like spline surfaces, directly in the simulation [4].
The purpose of this paper is to investigate the use of cell based importance sampling technique (particle splitting with Russian Roulette) in MC shielding calculations of a stellarator type geometry. The aim is to demonstrate that this method is a suitable Variance Reduction (VR) technique which can be adopted to the complex spline geometry of the HELIAS model.

2. Variance reduction methods

Any result of a Monte Carlo calculation is subjected to a statistical error. It can be expressed as an estimated relative error at the 1σ level with $R = S_{\bar{x}}/\bar{x}$, where $S_{\bar{x}}$ is the standard deviation of the mean and $\bar{x}$ is the estimated mean. For a well-behaved tally is R proportional to the number of histories N, were $R = 1/\sqrt{N}$. This error reflects only the statistical precision of the MC calculation and not the accuracy of the result compared to the true physical value. For MCNP, relative statistical errors below 10% are considered as generally reliable, except for point detectors [5]. The relative error $R = C/\sqrt{T}$, where C is a positive constant and T is the computational time proportional to N, can be reduced in two different ways: either increase T and/or decrease C. Typically the computational resources are limited which does not allow to heavily increase the computational time. Special variance reduction techniques are implemented in MCNP to enable decreasing C, where C depends on the tally choice, i.e. the type of registration of further information during the simulation, and/or the sampling method choices.
The standard MCNP calculation uses the analogue MC method without any variance reduction. The analogue technique uses the natural probabilities that various events, like collision, fission or capture, occurs. The particle transport is directly analogous to the natural event probabilities. This method works well when a significant fraction of particles contributes to the tally result, but fails if the fraction of particles detected is very small. In this case the statistical uncertainty of a tally is unacceptable high and methods to improve this are needed.
In contrast, the non-analogue MC method follows “interesting” particles more often than “uninteresting” ones. An “interesting” particle is one that contributes a large amount to the quantity of interest which needs to be estimated. The non-analogue techniques increase the chance that a particle scores in an area of interest [5].
There are many different variance reduction techniques in MCNP, but only the particle population control method is used in this paper. Herein particle splitting and Russian Roulette are utilized to control the population number across the calculation geometry. Particle splitting means that particles entering more important regions are split into sub particles. At the same step the weight is distributed equally to the sub particles by preserving the total weight of the entering particle. Russian Roulette means that particles entering a cell with less importance were either killed with a probability of $1 - v$ or survive with the probability v and their weight will be multiplied by v^{-1} [6]. From this follows that in important regions many particle with less weight per particle contribute to the result, while in less important regions less particles with higher weights were tracked.

3. Application to a simplified geometry

The stellarator geometry, as seen in figure 1, is large and complex. A simplified geometry, which was prepared to verify three different CAD to MC geometry translation methods [2], is used for all neutronic calculations in this paper and can be seen in figure 2. The components, starting from the plasma to the vacuum vessel, and their corresponding homogenized materials are presented in table 1.

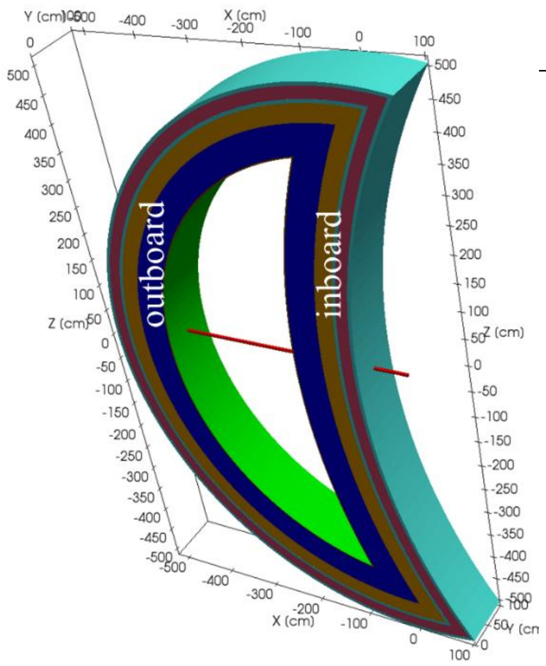

Figure 2: Verification geometry with layers, the red line indicates the tally locations used for the verification calculations [2]

Component	Thick-ness [cm]	Material
Tungsten Armor	0.2	Tungsten
First Wall	2.5	Eurofer and Helium
Breeder Zone	50	Homogenized "Helium Cooled Pebble Bed" (HCPB) mixture [7]
Back Support Structure	30	Eurofer and Helium
Inner Vacuum Vessel	6.0	Steel (SS316-IG)
Vacuum Vessel Shield	20	60% Steel and 40% Water
Outer Vacuum Vessel	6.0	Steel (SS316-IG)

Table 1: Radial build of the verification geometry at the mid-plane starting at the plasma chamber

The thickness of the breeder zone, back support structure and vacuum vessel shield is very large to apply the cell based variance reduction methods. These zones were separated into $5\ cm$ layers in respect to the mean free path of the neutrons in these materials.
A volumetric $14.1\ MeV$ neutron source is included inside the plasma chamber to fill up the whole space in Y-direction with a total length of $100\ cm$. Reflecting boundary conditions are set both on $y = 0\ cm$ and $y = 100\ cm$ of the simplified geometry [2]. The homogenized material layers, presented in table 1, are the same as integrated in the CAD model of HELIAS.

The neutron flux in regions far away from the plasma chamber have a high statistical uncertainty when calculated with the analogue MC technique. The application of a VR method should decrease these uncertainties and at the same time not increase the consumption of computational resources. There are different variance reduction methods available in MCNP, as described in chapter 2. The aim of the analysis in this paper is to use the VR technique most-suited for the later application in HELIAS calculations. The application of the weight window generator in a computational problem is a widely used method for VR, which cannot easily be utilized for HELIAS.

The HELIAS geometry is complex, and the generation of a weight window is very difficult. In respect to this, it is important to investigate a simpler, manual applicable VR approach with the simplified geometry, which can be applied later to HELIAS.
A possible solution is the use of the cell based importance sampling technique with particle splitting / Russian Roulette and manual specification of the cell importances. The layered construction of the stellarator, as presented in table 1, as well as no angular dependency of the source description offers the adaptation of this method. Regions close to the plasma chamber will have a lower cell importance compared to regions far away. MCNP will automatically split particles entering from a lower cell importance to a higher one, as long as the cells contain material, and lowering the weight of each particle while preserving the total weight. More particles can contribute to the result in the area far away from the plasma chamber and can decrease the relative statistical error. This method only works properly and provides a good particles splitting, if the step from one cell importance to another one is not too large. The general approach is to increase the number of particles as the particle population decreases across a distance, which corresponds to the average mean free path of a neutron. A recommendation by the MCNP developers [5] is to choose the increase of the importance from one cell to the next not larger than a factor 4. The larger this difference is the more particles will be generated when crossing the cell boundary and the weight of the split particle is equally distributed to all newly generated particles. That might generate results with low statistical error, but with an artificial high particle population and biased tally results when applying a too large step size.
It is important to have a look on the neutron flux and its corresponding relative error at the indicated location on figure 2 in the outboard side, to get an idea of how the factor of the increased cell importance should be used. The decrease of the neutron flux and simultaneously increase of the corresponding relative error can be seen in figure 3 for an analogue simulation.

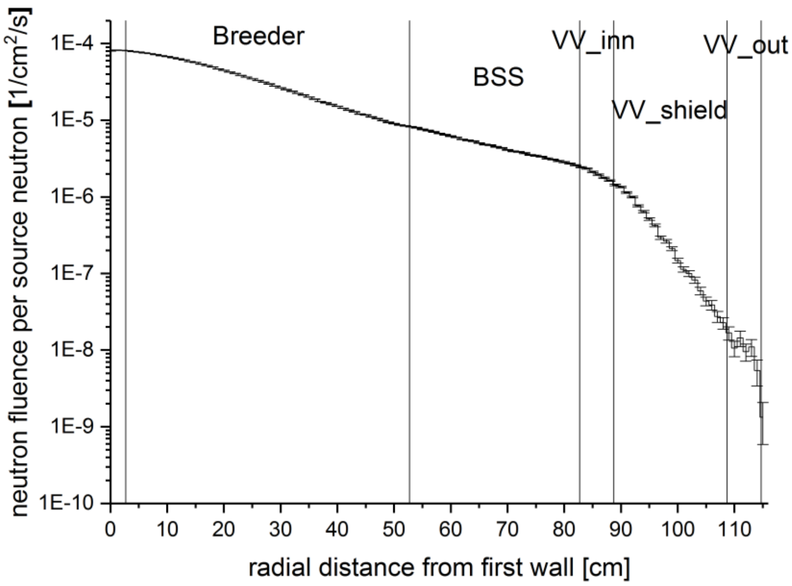

Figure 3: Neutron fluence per source neutron in dependency of the radial distance from the first wall including its corresponding relative statistical error.

It can clearly be seen in figure 3 that the neutron flux decrease in the breeder layer and the back support structure is around one order of magnitude, respectively. The decrease in the vacuum vessel shield is the largest by approximately three orders of magnitude. The increase of the statistical error in regions beyond the back support

structure can also be seen. These are the regions of interest when applying variance reduction methods.
The increasing of the relative statistical error in areas beyond the back support structure indicates that less particles contribute to the result. When applying VR methods, the particles were guided in these areas to lower the relative statistical error.

Three different importance settings are considered for applying a cell based variance reduction technique by increasing the cell importance in material cells. The general approach is to get a flat neutron population and thus increase the cell importance as the neutron flux decreases. Two of the options are applied to the geometry in figure 2 without additional cell splitting, and one option is applied with additional cell splitting of $5\ cm$ in the breeder zone, back support structure and vacuum vessel shield. Each of these options uses an increase of the cell importance by a fixed factor. The options are: double and quadruple (original geometry), and refined (with cell splitting). As the name indicates the increase factor of quadruple is four, all others have an increase factor of two. An overview is shown in table 2.

Table 2: Comparison between different material importance settings in respect to the component.

Component	Importance Setting			
	Normal	**Double**	**Quadruple**	**Refined**
Tungsten Armor	1	1	1	1
First Wall	1	2	4	1
Breeder Zone	1	4	16	1, 1, 2, 2, 4, 4, 8, 8, 16, 16
Back Support Structure	1	8	64	32, 32, 64, 64, 128, 128
Inner Vacuum Vessel	1	16	256	256
Vacuum Vessel Shield	1	32	1024	512, 1024, 2048, 4096
Outer Vacuum Vessel	1	64	4096	8192

All importance changes in table 2 have an impact on the relative statistical error of the simulation, whereas the values for the neutron flux stay the same. It is also important to check the neutron population in every material layer, a disproportion in the decrease of the neutrons in the areas far away from the plasma zone points to a not correctly chosen importance setting.

4. Computation and Results

Two different run time criteria were chosen to compare the relative statistical error to each other. As a first test, a fixed number of starting particle histories (10^9) were calculated, and as a second test a fixed computational time with 24h on 200 CPU cores was used.
Results for the calculations with the fixed number of starting particles are presented in table 3 and figure 4.

Table 3: Comparison between the increases of the computational time and the decrease of the relative statistical error at the outside of the outer vacuum vessel of different cell importance settings by a fixed number of particle histories.

Importance Setting	**Computational Time [min]**	**Time Increase Factor [compared to "Normal"]**	**Relative error at outside "VV_out"**	**Error Decrease Factor [compared to "Normal"]**
Normal	2.4×10^5	1	0.50382	1
Double	9.9×10^5	4.13	0.05932	8.49
Quadruple	4.0×10^6	16.67	0.00769	65.52
Refined	2.1×10^6	8.75	0.00529	95.24

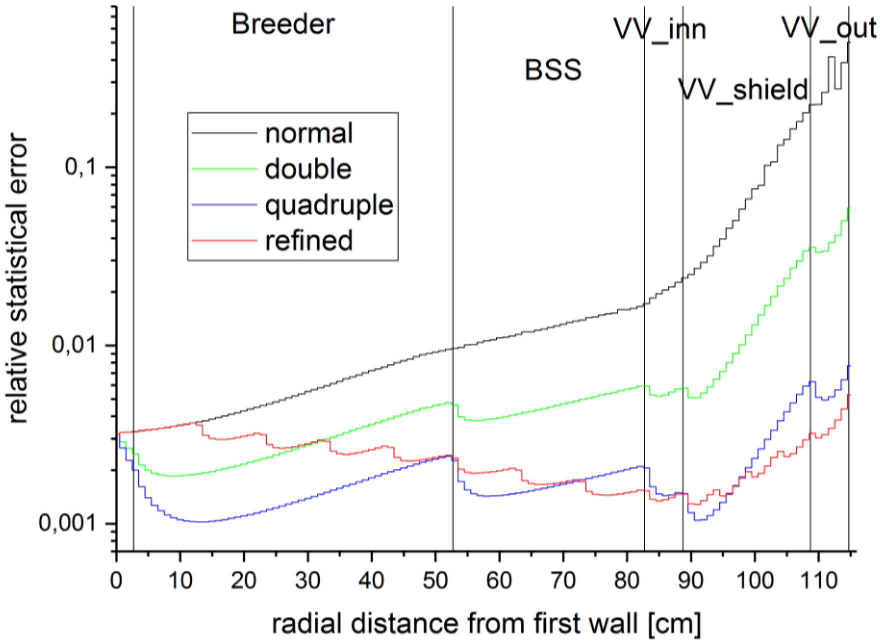

Figure 4: Relative statistical error at the outboard side of the MCNP calculation with 10^9 source particles.

It can be clearly seen in table 3 that on the one hand the computational time increases up to a factor of ~16 between the "Normal" and "Quadruple" importance setting. On the other hand, also seen in figure 4, is a decrease of the relative statistical error between the two settings of the importance setting with a factor of ~66 at the outside of the vacuum vessel at $x = 116\,cm$. The highest decrease factor of the relative statistical error can be found between "Normal" and "Refined" with a factor of ~95. This means, that it is expected to calculate in the analogue simulation much longer to get the same results as in the "Refined" case, because the relative error $R = 1/\sqrt{N}$ decreases by an increased number of stating particles. The mentioned values for "Quadruple" and "Refined" are significant higher compared to the increase of computational time. In the graph "Refined" the additional cell spitting can also be seen, corresponding to the different cell importance, within one material layer.
Nevertheless is the comparison of the computational time with a fixed amount of starting particle histories not the best-suited criteria. If the VR method is applied sufficiently for the simulation, it can decrease the relative statistical error in less computational time, but this is not a main criterion in the selection of the best-suited approach. The second approach uses a fixed computational time to $t = 288000\,min$ to compare the devolution of the relative statistical error. The result is shown in table 4 and figure 5.

Table 4: Comparison between the decreases of the number of starting particles and the decrease of the relative statistical error at the outside of the outer vacuum vessel by a fixed computational time.

Importance Setting	**Number of starting particles**	**Particles Decrease Factor [compared to "Normal"]**	**Relative error at outside "VV_out"**	**Error Decrease Factor [compared to "Normal"]**
Normal	1.5×10^{10}	1	0.11961	1
Double	3.6×10^{9}	4.17	0.0308	3.88
Quadruple	6.6×10^{8}	22.73	0.00946	12.64
Refined	1.1×10^{9}	13.64	0.00499	23.97

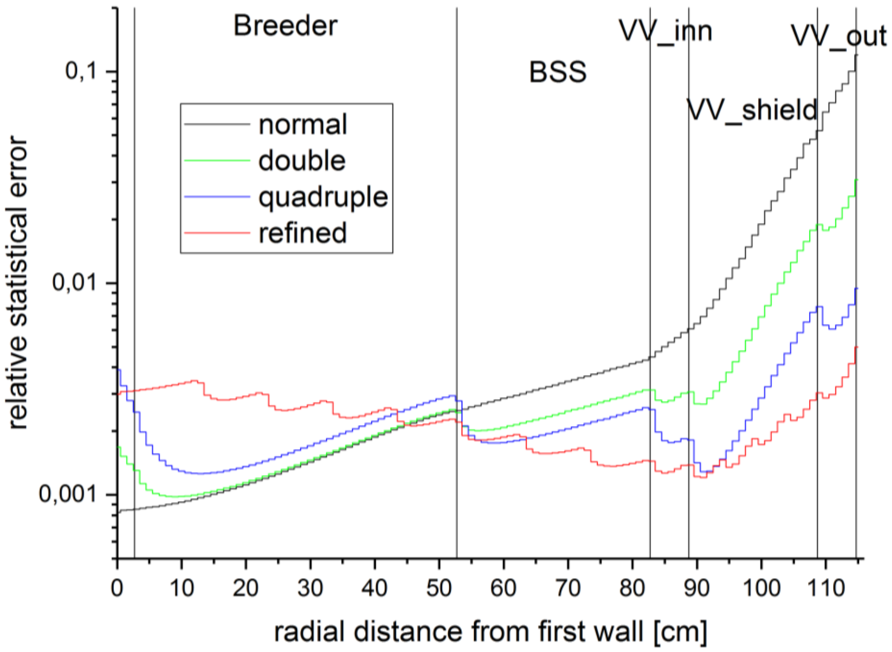

Figure 5: Relative statistical error at the outboard side of the MCNP calculation with a fixed computational time.

The initial starting point, at $x = 0\,cm$ of the curves in figure 5 is different, which is related to the different amount of starting particles shown in table 4. The lower the number of generated particles, the higher is the relative statistical error at this position. The graph "Refined" shows the same behavior in figure 5 as in figure 4 due to the very similar amount of starting particles for this cell importance setting. It can clearly be seen that the graph "Refined" shows its potential to decrease the relative statistical error in regions far away from the plasma, but not in regions close to the plasma, which has to be expected. The opposite is true for the graph "Quadruple", were the relative statistical error is decreased significantly in each material layer, except in the vacuum vessel shield. This case has the advantage that no additional cell splitting in the material cells have to be applied.

The neutron population shows in the "Normal" case a high decrease from plasma to the outside of the geometry, which is expected. This decrease could be prevent and transform to a nearly uniform distribution for the cases "Refined" and "Quadruple".

5. Conclusion

The application of variance reduction methods for a stellarator geometry is not straightforward. There are several options allowed in MCNP to apply these methods, which need to be carefully considered for each calculation problem. The manual setting of the cell importances is currently the best-suited method for the complex stellarator geometry to improve the relative statistical error in each material layer.

The results show a significant difference between non-VR and VR cases. The non-VR results are not acceptable in areas far away from the plasma chamber, in respect to the MCNP quality assurance criteria. For such regions, the VR methods must be applied to generate suitable results. It can clearly be seen that the application of VR methods will decrease the computational effort needed to reach acceptable statistics in regions far away from the plasma.

Next step is a further verification of this approach regarding the statistical reliability and the subsequent application to the real stellarator geometry and the investigation of the behavior of the relative statistical error for the neutron flux calculations.

Acknowledgement

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

This work was performed on the computational resource ForHLR II funded by the Ministry of Science, Research and the Arts Baden-Württemberg and DFG ("Deutsche Forschungsgemeinschaft").

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