Serpent neutronics model of Wendelstein 7-X for 14.1 MeV neutrons

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Abstract
In this work, a Serpent 2 neutronics model of the Wendelstein 7-X (W7-X) stellarator is prepared, and an instrument function for the Scintillating-Fibre neutron detector (SciFi) is calculated using the model. The neutronics model includes the simplified geometry for the key components of the stellarator itself as well as the torus hall. The objective of the model is to assess the 14.1 MeV neutron flux from deuteron-triton fusions in W7-X, where the neutrons are modelled only until they have slowed down to 1 MeV energy. The model indicates that the superconducting coils are the strongest scatterers and block neutrons from large parts of the plasma. The back-scattering from e.g. massive steel support structures is found to be small. The SciFi will detect neutrons from an extended plasma volume in contrast to having an effective line-of-sight.

Keywords: Wendelstein 7-X, Neutrons, Serpent, Scintillating Fibre, simulation

1. Introduction
In preparation for a future deuterium operation of the Wendelstein 7-X (W7-X) stellarator, potential neutron diagnostics must be evaluated. The Scintillating-Fibre (SciFi) neutron detector [1] can be used to detect the 14.1 MeV neutrons originating from tritium burn-up process, where tritons from DD fusion fuse with the bulk deuterium:

\[
\text{^2D} + \text{^2D} \rightarrow \text{^3He} + \text{^1n} (2.45 \text{MeV})
\]

\[
\text{^2D} + \text{^3He} \rightarrow \text{^4T} + \text{^1p}
\]

\[
\text{^3He} + \text{^1n} (14.1 \text{MeV}).
\]

The background of DD (2.45 MeV) neutrons and gamma rays are a challenge of the measurement. By measuring the tritium burn-up, the fast ion confinement of W7-X can be assessed. The fast ion confinement at high plasma pressure is one of the optimization targets of the W7-X design, and thus demonstrating it is a high-level project goal.

The state of the art neutronics model for W7-X is made by Grünauer [2, 3] with MCNP. While the materials are well defined, the geometry is highly simplified. The current work demonstrates the use of detailed geometry in the model. The neutron scattering in material reduces the energy and randomizes the travel direction of the neutrons. Thus, the scattering can disperse neutron flux traveling towards the detector (shielding) or reroute neutrons towards the detector (back-scattering), and thus detailed geometry in the proximity of the detector is important. DT (14.1 MeV) neutrons reaching SciFi below approximately 2.45 MeV energy are indistinguishable from DD-neutrons and are thus discarded.

The SciFi detector consists of an array of scintillating plastic fibres inserted inside parallel holes drilled into an aluminium cylinder. The high-energy neutrons scatter from the hydrogen in the plastic and the recoil protons induce scintillation in the fibre, which makes the detector insensitive to thermal neutrons. The light is guided to a photo multiplier tube for amplification and later detection. The parallel fibres induce a natural directionality to SciFi. The detection efficiency as a function of neutron streaming direction was measured at the Physikalisch-Technische Bundesanstalt (PTB), Germany’s national metrology institute, and is used as one of the inputs for this work.

The following section [2] describes the Serpent 2 [4] model created in this work, as well as how an instrument function for SciFi is calculated. The tabulated function facilitates calculation of SciFi signals for various neutron rates without re-running the whole neutron transport calculation. The section [3] shows key features of the calculated instrument function and a first estimate of the SciFi signal from a hypothetical deuterium plasma is given in the section [4]. The paper is concluded by a discussion and summary in section [5].

2. The W7-X model implementation in Serpent
A simulation model in Serpent consists of a description of materials, geometries, detectors and neutron sources. The material isotopic compositions and densities direct the use of scattering etc. cross sections, that were loaded, in this work, from the Joint Evaluated Fission and Fusion (JEFF) Nuclear Data Library 3.1.1. In the current model, the detectors are set up as

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track-length-detectors that tally the neutron flux within the detector, which is defined as the aluminum cylinder housing the scintillating fibres. The next section describes the geometry of the material boundaries and detector shapes used in the calculations.

2.1. Geometry

The Wendelstein 7-X stellarator consists of hundreds of thousands of components and many of them are custom 3D-designs. The computer aided design (CAD) model of the machine consists of 70 000 unique parts, many of which have 10 instances. The in-vessel parts cover 260 m$^2$ of surface, consists of about 250 000 parts, 4000 of which are major. All the surfaces are (or will be) actively cooled, with several kilometers of water lines in-vessel. It is practically impossible to introduce the whole complex CAD model into any current neutronics tool and expect to have a sufficiently fast model. Thus, it was necessary to pick the most significant components and only include them. Even these geometries required simplifications due to the extremely detailed 3D-designs of most components.

The model mainly consists of CAD models exported from the CATIA design database as .stp-files with minor details manually removed in CATIA. The .stp-files were then studied in FreeCAD, meshed, and saved in .stl-format. Serpent includes a .stl health check tool that reveals leaking or malformed surface meshes. The leak-locations were imported back to FreeCAD, and the broken details healed or removed. This was iterated until the meshed model was leak proof.

Further manual labor was needed for certain components. In particular, the inner vacuum vessel (VV) CAD model was unusable and, therefore, the VV model was recreated from simplified parametric representation lacking the port holes and the one for port AEU20 was recreated. Water cooling of plasma facing components was included by making rough estimates on one for port AEU20 was recreated. Water cooling of plasma facing carbon components (PFC): di-amating homogenized materials. The very simple model for the water facing components was included by making rough estimates on one for port AEU20 was recreated. Water cooling of plasma

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The model includes the following components (figure 1): the plasma domain; plasma facing carbon components (PFC); di-

2.2. Model optimization

The Serpent geometry engine is very powerful, when used correctly. The geometry can be defined as a combination of constructive solid geometry (CSG) and meshed surfaces from .stl-files. In the current model, there are approximately 3 million triangles. A good geometry definition divides the model into disjoint areas to allow Serpent to quickly narrow down to the relevant components. This was achieved by including the components in concentric universes so that the most often used component (plasma domain) was always checked first. Furthermore, Serpent uses search trees to expedite the mesh searching, and optimizing the search tree parameters improved the model speed further.

By studying the solid angles, it can be estimated that less than one out of 100 000 neutrons would reach the detector even when born in the most favorable locations of the plasma. Generating sufficient statistics in the whole plasma domain with reasonable energy resolution would take excessively long. Thus, it is necessary to bias the simulation to predominantly follow neutron histories that are likely to reach the detector and predominantly ignore the others [5] and Serpent uses standard Monte Carlo methods to achieve this [6]. To gain sufficient number of counts in the detector, the Serpent global variance reduction was used in a model without the PE collimator box and directionality. Next, the weight windows were optimized for gathering counts in the SciFi detector, still without the directionality. The resulting weight windows were used in the production runs and are presented in figure 2.

In the end, it was possible to calculate 868 histories per CPU-second from the initial energy of 14.1 MeV to the cut-off energy of 1 MeV. The meaning of the computation speed is obscured by the variance reduction algorithm in use. The code required 15 GB of memory per computing node.

3. SciFi instrument function calculation

The main goal of this work is to implement a method for calculation of the SciFi instrument function or weight function. That means a function that transforms a given fusion rate in a given location into the measured signal in SciFi. To achieve this, 14.1 MeV-neutrons are initialized uniformly with isotropic velocity distribution in the plasma domain. Their histories are followed in the above described geometry using the variance reduction methods.

![Figure 1: The modelled geometry. The model is toroidally 5-fold symmetric.]

![Figure 2: Variance reduction weight windows used to concentrate the simulation effort to the neutron histories likely to contribute to SciFi signal. (logarithmic scale 3×10^{-4} \cdots 3 \times 10^{2})]
In the SciFi, a track-length-detector tallies the average neutron flux inside the SciFi:

$$\Phi_{\text{det}} = \frac{1}{V_{\text{det}}} \int_{0}^{\infty} \theta \omega d\tau,$$  

where $w$ is the neutron marker weight depicting how many real neutrons per second the marker represents. The anisotropic detection efficiency, $\theta$, of SciFi scales the neutron flux as a function of the angle between the SciFi axis and the neutron track. The whole SciFi aluminium cylinder is used as a proxy for the active media, the fibres, to increase the integration volume. The flux $\Phi_{\text{det}}$ is binned in a cylindrical grid as a function of the marker birth location.

From the flux one gets to the counts by integrating an (arbitrary) neutron production rate $S$ weighted by the instrument function over the plasma volume.

$$\frac{\text{counts}}{s} = \sum_{\text{bins}} \int_{V_{\text{bin}}} A_i \Phi_{\text{det}} \frac{V_{\text{plasma}}}{N V_{\text{bin}}} \int_{S} dV,$$  

where $A_i$ is the effective active area of the SciFi detector measured experimentally at PTB (1.2 mm²), and is simply the efficiency of which SciFi counteract results from a certain neutron flux into the detector. Serpent launched $N$ neutrons per second in the whole plasma volume $V_{\text{plasma}}$ which needs to be distributed to the bins according to their volumes ($V_{\text{bin}}$).

To assess the relative significance of the various components, the calculation was repeated with certain components removed.

The resulting instrument function is stored in a regular cylindrical grid with vertical and radial grid pitch of 10 cm and toroidal pitch of 2°. The fusion rate is expected to peak near the stellarator magnetic axis, so a natural visualization is to show the instrument function along the axis as a function of the toroidal angle. Figure 3 shows this for four different neutron track energies and for the calculations with specific components removed. The detection efficiency is toroidally wide, i.e. the "line-of-sight" through the port and collimator is not evident. This is explained by noting that approximately half of the counts are due to neutrons with energy below 10 MeV, i.e. after scattering in matter before reaching the detector. Also the PE collimator dimensions indicate a wide cone: a 20 cm deep, $\varphi$ 4 cm collimator will lead to an approximately 50 cm diameter acceptance cone at 3 m distance. The various components all act to reduce the neutron flux to the detector. For scattered neutrons, the coils are the largest shadowing element. Back-scattering from the ring or water containing plasma facing components (PFC) appears small.

If the spatial dependency is dropped, it is possible to significantly increase the energy resolution and study the energy spectrum of neutrons reaching the SciFi detector, as illustrated in Figure 4. It is obvious that only a tiny fraction of neutrons reach the detector without scattering while in transit. No component increases the flux significantly, not even the massive steel ring on the opposite side of the plasma to the detector. A minor back-scattering signal (positive values in Figure 4) may happen due to scattering in the concrete torus hall walls or in the collimator.

The ultimate use of the instrument function is to estimate SciFi signal due to a real plasma using equation. As a proof of concept, the fusion rate is calculated using the ASCOT suite of codes, as described in [3]: The neutral beam injection of

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1. A Serpent 2 feature implemented by the author for this work.
2. Another Serpent 2 feature implemented by the author for this work.
deuterium is modelled with BBNBI, their slowing down with ASCOT5, the ensuing D(D,p)T reaction rate is calculated with AFSI. The triton slowing down is again calculated with ASCOT5, the ensuing D(T,α)n reaction rate. Serpent then calculates the neutron flux at the SciFi detector. The flux is converted to counts using the anisotropic detection efficiency calibration measured at PTB.

The result is 158 counts/s from triton burnup neutrons in a hypothetical Wendelstein 7-X plasma heated by 8 NBI sources (12 MW tot) having axial density of 1023/m3 and temperature of T=1.4 keV producing 1.6 × 1012 n/s. Thus, an estimated SciFi integration time could be 50 ms. Table 1 shows how these counts are distributed to different energies. The 14.8 MeV detection efficiency is used for all energies. A more refined energy dependent calibration would likely lead to higher count rates. With the current settings for pulse discrimination, the effective active area of SciFi increases when the neutron energy drops from 14.8 MeV to 2.49 MeV and the directionality is reduced.

5. Discussion and Summary

This paper demonstrates that it is possible to generate a Monte Carlo neutronics model of a complex 3D shaped stellarator using the Serpent 2 code. The model is used to calculate an instrument function for a scintillating fibre neutron detector. The detector is found to be wide-angle, in the sense that it detects 14.1 MeV neutrons from a large volume, not only from a "line-of-sight". This is because most neutrons reach the detector only after scattering. However, little back-scattering of neutrons is found, meaning, removal of any component from the model increases the counts in SciFi. This would imply, that by adding further components the model will further reduce the SciFi signal, and thus the integration time estimate for SciFi (50 ms) is probably a lower bound.

Future work includes introducing missing components and applying the model to various calculated neutron rates to assess the capability of the system to detect variations in the neutron rate caused by various experiments.

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| Bin limits (MeV) | Counts/s |
|------------------|----------|
| 2.5              | 40       |
| 5.0              | 35       |
| 10.0             | 16       |
| 12.5             | 67       |

Table 1: The energy spectrum of the neutron counts (158 tot). The results show number of DT neutrons per second detected by SciFi. The energy depicts the energy of the originally 14.1 MeV-neutrons when it arrives to the detector. (The 14.8 MeV detection efficiency measured at PTB is used for all energies.)