THEA ENERGY

Neutronics Modeling and Simulation for Thea Energy's DD Stellarator

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Introduction

Neutronics modeling and simulation plays a crucial role in evaluating the performance and safety characteristics of fusion reactors. Thea Energy's first stellarator device, Eos, will operate with DD plasma with uniformly distributed neutron energy range between 1.5 and 3.7 MeV. This configuration presents a unique set of neutronics challenges compared to the typical DT designs, where the neutron energy is typically 14.1 MeV.

Methodology

Using the OpenMC Monte Carlo particle transport code [1], we modeled various blanket configurations, materials, and thicknesses, allowing for the investigation and optimization of key neutronics parameters, such as: tritium breeding ratio (TBR), neutron flux distribution, neutron absorption, and component heating. Initial modeling and simulation efforts utilized spherical geometry, and latter models were done on a stellarator shaped CAD geometry.

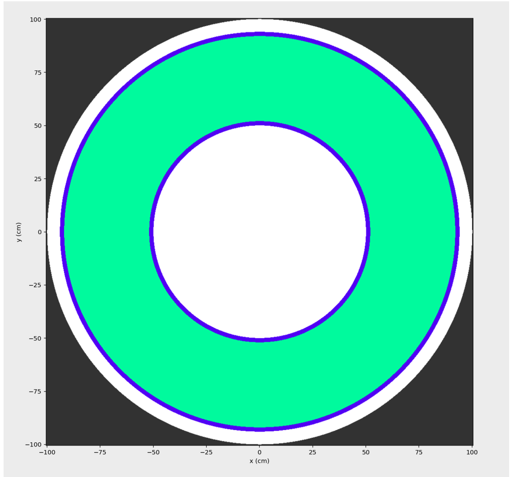

Figure 1: Spherical geometry with a fixed 2.5 MeV neutron source at (0,0,0).

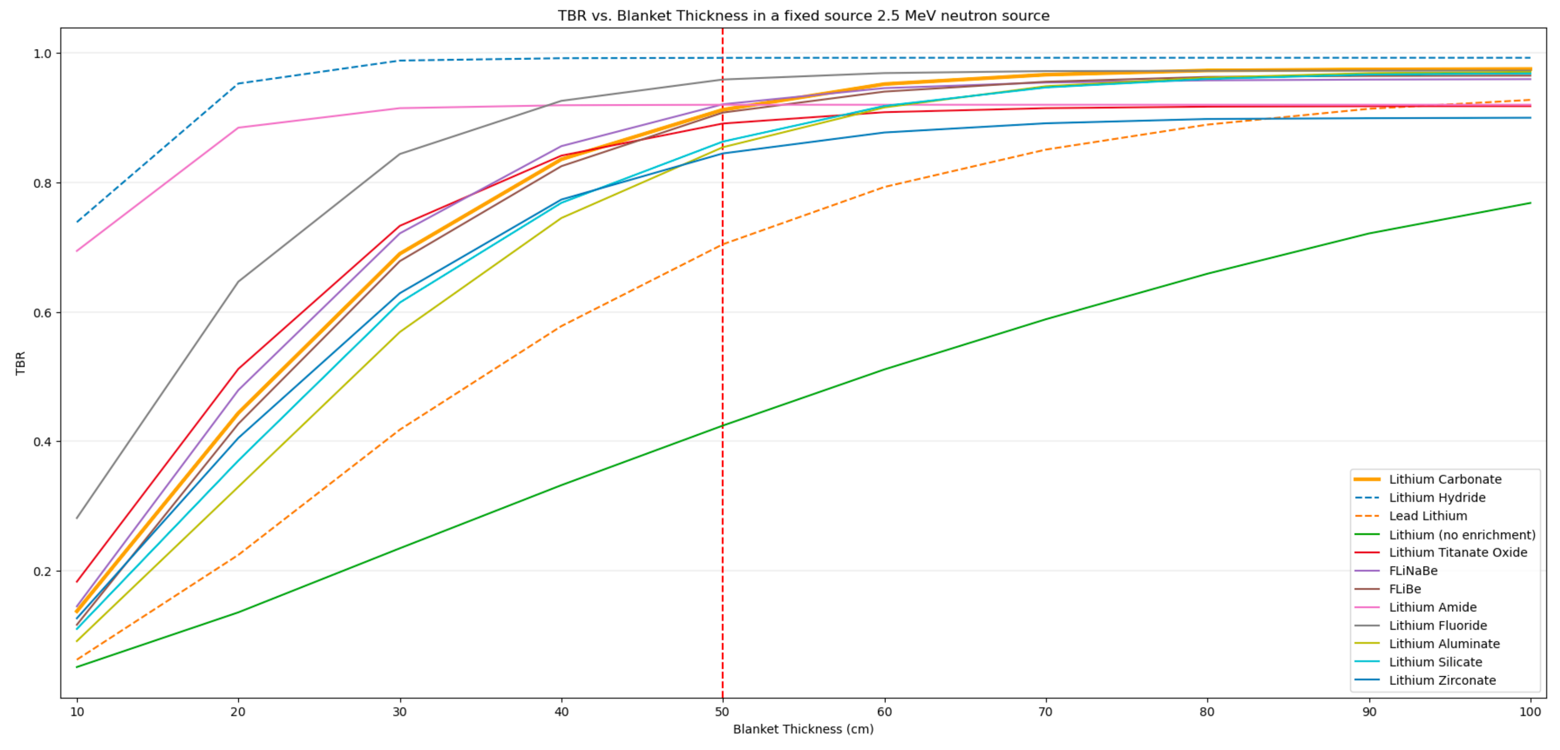

Figure 2: The graph compares various lithium-based compounds for TBR under a fixed source of 2.5 MeV DD neutron spectra. Note: all materials depicted are *not* enriched.

Lithium Carbonate: Our Material Choice for Breeder Blanket

While other materials such as Lithium Hydride and Amide exhibited the highest TBR, they were impractical due to their hazardous properties such as high flammability, reactivity, and spontaneous ignition risks. We chose Lithium Carbonate (orange, bolded line in Figure 2) as our choice of breeder material due to its economical feasibility, easy accessibility, and safety in handling. (Side note and fun fact: lithium carbonate is listed on the World Health Organization's List of Essential Medicines and is commonly used in treating mood disorders. It's safe to eat and available at local pharmacies like CVS or Amazon) [2]. At breeder thickness of 40-50cm, lithium carbonate is competitive in its TBR production compared to other options available [3].

Takeaway: 50cm blanket meets shielding & TBR requirements

Through extensive testing of various blanket configurations, considering key factors like tritium breeding ratio (TBR), neutron flux, and leakage, we determined that the 50cm blanket design fulfills the requirements for our compact DD stellarator design. The blanket, equipped with a lithium carbonate breeding layer meets our shielding and tritium production needs for Eos.

Fluence results on the stellarator HTS magnets

The fluence across the HTS magnets are under the limits imposed by current literature on the effect of fast neutron irradiation on REBCO tape in ref. [6]. While initial indications suggest acceptable fluence levels, further in-depth modeling and simulation and rigorous fusion-relevant experiments are needed to be conducted on the REBCO tape and HTS magnets themselves to solidify these preliminary findings and ensure they can endure the envisioned 30-year lifespan of the reactor.

Parametric Stellarator Geometry Creation

We have written python scripts to automate the parametric geometry creation and meshing. Our CAD models are generated using `build123d`, a python wrapper around the OpenCASCADE geometry kernel. The mesh is created using an internal tool called `Stellarmesh` [4]. For the CAD models, a line source in the shape of the plasma was implemented, as shown in the figure below. For these CAD models, neutrons are isotropically along the line source, and are emitted at a fixed-source of 2.5 MeV energy.

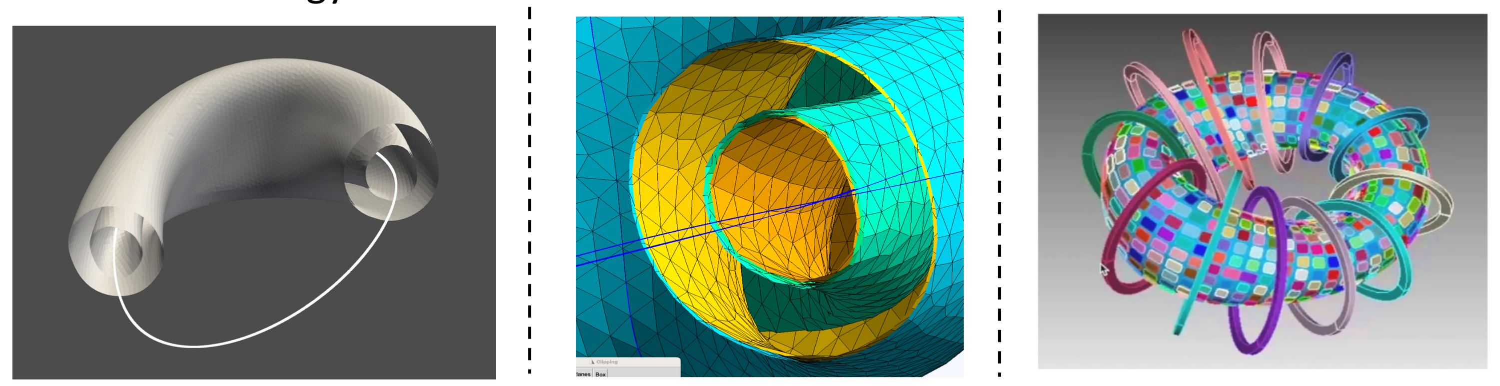

Figure 3, 4, 5: A few example of CAD models of the stellarator design. Left to right: simple geometry depicting a line neutron source in the shape of our plasma; middle: example of a triangular mesh on the CAD geometry. Please see A. Koen's poster for details on Thea Energy's geometry creation. Ref [5]. Finally, the right-most picture is a visual depiction of the full Thea Energy stellarator model.

Stellarator Neutronics Modeling & Simulations

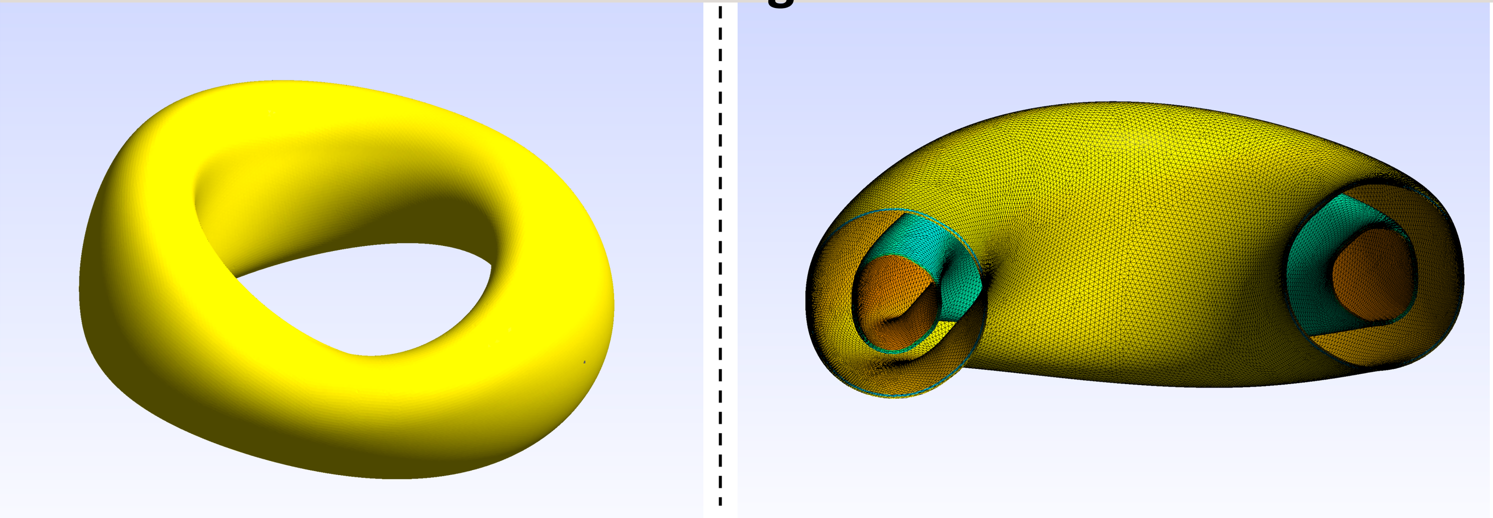

Figure 6, 7: Simplified initial CAD models for the blanket design. All layers are offset on top of the plasma.

Table 1: Stellarator Blanket Design. Note: Total Blanket thickness is fixed at 50cm.

Geometry Description	Li_2CO_3 Thickness	TBR	Leakage Fraction
50cm breeder layer only	50cm	0.94	0.059
2cm FW, 46cm breeder, 2cm LW	46cm	0.93	0.052
2cm FW, 2cm mod, 42cm breeder, 2cm mod, 2cm LW	42cm	0.85	0.029
8 times alternating: 5cm breeder with 1cm mod; and 1cm FW, 1cm borated steel LW	40cm	0.98	0.012

Table 1: portrays a subset of over 30 distinct geometry iterations involving diverse moderators and absorber materials. All blanket designs are held at a fixed 50cm thickness. The moderator shown in the table is PEEK ($C_{19}H_{14}O_3$). The goal was to optimize blanket design for efficient tritium breeding and low neutron flux on the HTS magnets. Acronyms are as follows:

- FW = First Wall
- LW = Last Wall
- mod = moderator.
- breeder = lithium carbonate

Streaming Studies: Modular Stellarator Design, 1mm slit

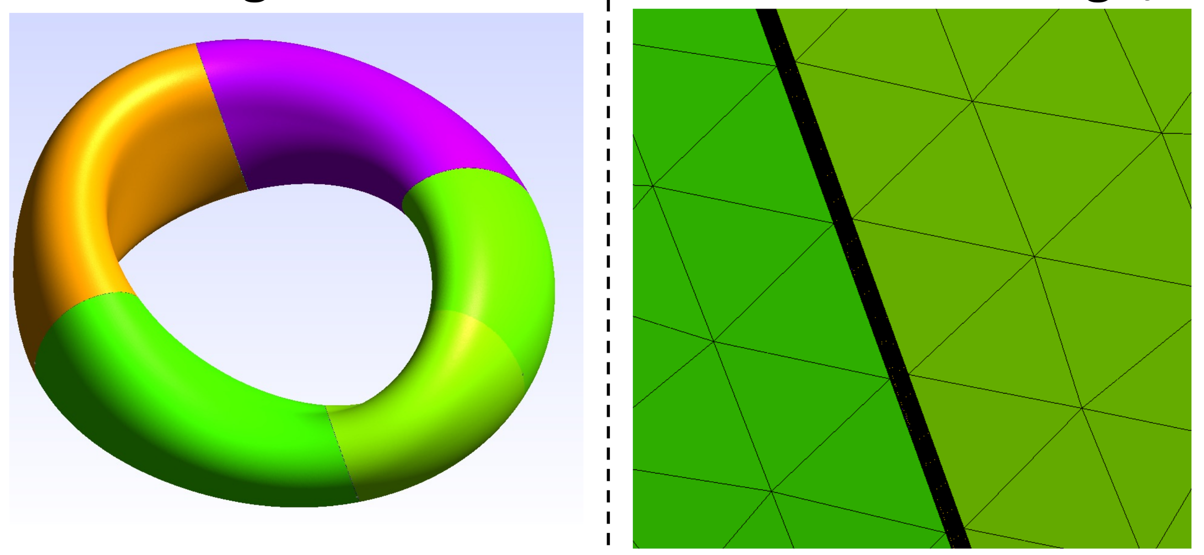

Figure 8, 9. Stellarator model without magnets, showcasing the 1mm slits split into 4 quadrants. Right: zoomed in triangular mesh showing the 1mm gap.

Table 2: Modular Stellarator Geometry with 1mm slits

Geometry Description	Li_2CO_3 Thickness	TBR	Leakage Fraction
2cm FW, 46cm breeder, 2cm borated LW	46cm	0.52	0.12
8 times alternating: 5cm breeder with 1cm mod; and 1cm FW, 1cm borated steel LW	40cm	0.45	0.025

Table 2: Neutron streaming studies incorporated 1mm gaps in the stellarator geometry to account for the modular design and any ports or diagnostics that may lead to neutron leakage. Please note that these are preliminary results on simplified models (as pictured), and further optimization is needed.

Other Neutronics Considerations

We are continuously refining our designs to exceed safety and performance requirements for our stellarator design. Our short and long-term next steps include:

- Use neutron source with uniformly distributed energy range of 1.5 to 3.7 MeV, instead of the fixed-source 2.5 MeV neutron source
- Explore coolant design options, such as water or helium-cooled blankets
- Conduct CFD calculations for neutron heat deposition and coolant flows
- Analyze gamma-ray distribution through the stellarator
- Establish stringent safety limits, covering prompt dose fields, instantaneous limits (e.g., nuclear heating to case/winding pack), and further calculations and lifetime optimizations based on neutron fluence to the HTS magnets.
- Conduct real-world experiments to test tritium migration in a lithium carbonate breeder blanket. Check for tritium accountancy by checking ease of tritium recovery
- Material compatibility tests and irradiation behavior at high temperatures and radiation environments

Conclusions

These simulations considered various blanket configurations, materials, and thicknesses, allowing for the investigation and optimization of key neutronics parameters, such as: TBR, neutron flux, heat deposited, neutron absorption and currents. We are also developing preliminary streaming studies models to ensure a modular stellarator design and find proper placement of diagnostic equipment and ports. The results obtained through this study will serve as a foundation for further optimization and design refinements, guiding the development of safe, modular, and efficient stellarator designs.

References

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[3] Dalton, A. W., Woodley, H. J., & McGregor, B. J. (1987). *Tritium breeding experiments in a fusion blanket assembly using a low-intensity neutron generator* (No. AAEC/E--642). Australian Atomic Energy Commission Research Establishment.

[4] A. Koen, "Automated Methods for Stellarator Modeling and Simulation". 65th APS-DPP, Oct 30, 2023. Stellarmesh library: https://github.com/Thea-Energy/stellarmesh

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[6] Fischer, D. X., Prokopec, R., Emhofer, J., & Eisterer, M. (2018). The effect of fast neutron irradiation on the superconducting properties of REBCO coated conductors with and without artificial pinning centers. Superconductor Science and Technology, 31(4), 044006

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