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TOWARDS A STELLARATOR FUSION REACTOR: ACHIEVEMENTS OF THE EUROPEAN STELLARATOR PROGRAM

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Abstract

Within Europe, the EUROfusion Task on Stellarator Power Plant Studies (SPPS) has taken on the role to develop the engineering basis for future Stellarator fusion reactors. However, the 3D geometry of Stellarators poses a unique challenge in the analysis and design process requiring novel and flexible tools capable of handling such complex geometries. To tackle this challenge, this activity successfully developed a wide range of new tools such as parametric CAD models as well as advanced 3D engineering models, most notably in the area of neutronics and magnet assessment among others. These developments allow to shorten the time between high level design iterations on the way to a pre-conceptual Stellarator reactor design. In particular, with our toolchain it is now possible to start from a fresh magnetic field configuration, automatically generate a corresponding CAD model with blanket layers, on which multi-physics assessments can be directly carried out, i.e. neutronics, electromagnetics, thermo-hydraulics, etc. This process will be demonstrated on the example of a newly conceived, turbulence optimized quasi-isodynamic Stellarator configuration, but can be applied without restriction to any potential future magnetic field candidate.

1. INTRODUCTION

Achieving controlled nuclear fusion remains a defining challenge of our time, with the potential to provide virtually limitless, clean energy. To date, the tokamak has been the primary focus of global fusion efforts, culminating in the ITER project and the design of the DEMO demonstration power plant.

Yet there is a compelling alternative: the stellarator. Unlike the tokamak, the stellarator offers steady-state operation without relying on large plasma currents, making it inherently free from disruptions and current-driven

instabilities. This advantage has gained renewed attention following the success of the Wendelstein 7-X (W7-X) experiment in Germany, which demonstrated the feasibility of highly optimized stellarator configurations.

In recognition of its promise, the EUROfusion consortium initiated the Stellarator Power Plant Studies (SPPS) task within its Prospective Research & Development program. SPPS aims to advance the stellarator as a credible fusion power plant option—bridging gaps in both physics and engineering integration [1].

Recent years have seen significant breakthroughs in stellarator theory and design, with new magnetic configurations achieving improved fast-particle confinement and reduced neoclassical transport—two long-standing limitations. This progress has enabled turbulence suppression by design, opening unique optimisation pathways unavailable to tokamaks [2]. The surge in innovation has also sparked private-sector interest, with as many stellarator startups emerging as tokamak-based ventures.

However, critical gaps remain. Stellarator research still lacks comprehensive integration of physics and engineering, particularly in areas like divertor design and edge plasma simulation—essential for reactor-scale devices. Engineering challenges are equally pressing: high magnetic fields, strong neutron loads, and complex remote maintenance requirements demand novel solutions.

SPPS addresses these challenges head-on, aiming to develop the tools, designs, and strategies needed for the next-generation stellarator. This paper presents an overview of SPPS's recent activities related to developing a workflow for design iterations. Starting with a magnetic field configuration as input, a blanket geometry is automatically generated (Section 2), which can be directly used in neutronics simulations (Section 3). Moreover, starting from coil filaments, a finite winding pack can be generated using magnetostatic analysis (Section 4).

2. PARAMETRIC GEOMETRY GENERATION FOR STELLARATORS

This section introduces briefly the SBGeom package, a tool for generating parametric geometries. Some of its features were briefly discussed in [3] and in more detail in [4]. SBGeom can create both uniform and non-uniform blanket components with high-quality meshes, design coil surfaces that make efficient use of the space around the plasma, generate finite-size coils, and export the geometry to formats compatible for e.g. neutronics or magnetostatic simulations.

2.1. Blanket Geometry

For creating blanket layers for arbitrary stellarator configurations, SBGeom takes as input the Last Closed Flux Surface (LCFS) in its typical (VMEC-like) Fourier representation. To generate components that extend beyond the plasma boundary, a way to measure distance from this surface is introduced using local surface normal's. This allows for the creation of offset surfaces used in building reactor components like blankets and coils.

However, extending surfaces from the LCFS by surface normals presents two challenges:

- **Coordinate Misalignment** – The normal direction used for extension can shift points away from the intended angular position.
- **Non-uniform Meshes** – Equal spacing in standard coordinates can lead to distorted or uneven meshes.

These can be partly mitigated either keeping the angular position fixed at the cost of distorting the radial distance, or alternatively preserving the radial distance, but adjusting the angular position.

However, the most effective solution is to use a Fourier transformation that converts the discrete points generated from surface normal's into a parametric surface, which can be arbitrarily meshed, an example is shown in Fig. 1. This approach enforces symmetry, keeps coordinates consistent, and ensures smoother, more uniform meshes. It also enables the definition of complex, layered blanket structures.

Finally, SBGeom can fit arbitrary surfaces beyond the LCFS—such as coil winding surfaces—by mapping their spatial coordinates back to the underlying parameter space. This makes it possible to parametrize and manipulate these surfaces efficiently for reactor design.

The geometry can be exported to the standard CAD formats as well as to DAGMC .h5m files.

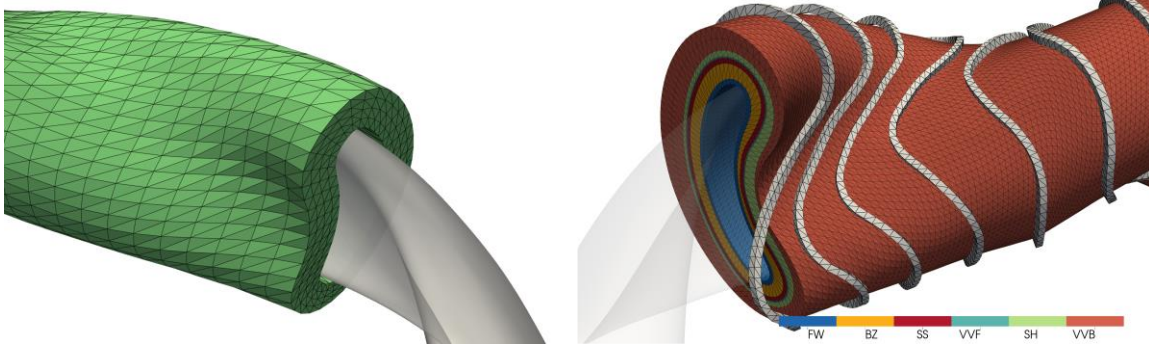


Figure 1: Left: Tetrahedra mesh of a volume that extends beyond the LCFS with a fixed distance. Right: Consecutive layers of First Wall, Blanket, etc. as generated and meshed with SBGeom.

2.2. Coil Geometry

SBGeom supports two types of coil representations as input:

- Discrete filaments (coils made up of individual points), and
- Fourier-based filaments (described using Fourier coefficients)

The formats can be converted from one to another with an option to ensure that the points are spaced evenly along the coil's length.

To create coils with a physical thickness (finite size), one need to define a coordinate system (called a frame) along the coil. SBGeom offers several ways to do this:

- The Frenet-Serret frame (not recommended, as it can lead to unstable or irregular shapes),
- The centroid frame, which uses the coil's direction and the vector to its center of mass,
- The rotation-minimized frame, which reduces twisting,
- Normal's based on the nearest point on a Fourier surface,
- Or, custom user-defined normal's.

It should be noted that none of these options involve optimizing the coil design for engineering or physics goals, which is done separately (see Section 4).

3. DETERMINISTIC NEUTRON TRANSPORT SIMULATIONS

In recent years, the standard Monte Carlo Neutron Transport codes have been applied to stellarators [5-7] and efforts have been undertaken to directly import the blanket geometry as generated by SBGeom (Section 2). Despite this success, the Monte Carlo approach remains computationally demanding and design iterations are not straightforward. To address this gap, we have developed a deterministic neutronics code that is computationally cheaper, directly integrated with the SBgeom geometry generation and can therefore be directly used for optimisation applications.

The details of the deterministic neutronics model are explained in detail in [8], but it generally relies on a typical phase space discretisation using a multi-group energy approach, discrete ordinates, and a tetrahedral mesh. A arbitrary order discontinuous Galerkin method is used as solver using Matrix-free iterations methods. The multi-group energy cross sections are obtained from 1D simulations of the blanket using OpenMC [9], which also generates appropriate heating and tritium breeding cross sections. Furthermore, the tetrahedra mesh can be directly imported to the deterministic code allowing neutron transport simulations directly on the meshed geometry without further simplifications (assuming a high enough spatial resolution).

We demonstrate the power of these new tools by executing a workflow that starts from a new magnetic stellarator configuration as input, generating a layered blanket geometry with SBGeom and then directly perform neutron transport simulations on the mesh using the deterministic approach, as indicated in Fig. 2.



Figure 2: Example workflow starting from a new stellarator magnetic configuration, generating layered blanket structures and performing directly neutron transport simulations on it.

A number of new, promising stellarator configurations have been conceived over the last few years. Here, we have opted for a so-called SQUID configuration [2, 10] as it combines a comprehensive list of optimisation criteria such as fast particle confinement, low neoclassical transport, and turbulence stabilisation, among others, and a preliminary coil-set is available. Ultimately, configurations are actively evolving and in that context, the selection here serves just an example.

The results of the neutron transport simulations are provided as a set of poloidal cuts in Fig. 3. As usual in stellarators, fitting a equidistant blanket everywhere is challenging, in particular on the inboard side, where some adjustment were necessary (light-blue to light-red region). Beyond the blanket layers, a large vacuum space was assumed to fill the space between blanket and coils (dark blue region). This strongly irregular space stems from the large coil excursions of the preliminary coil set and our ambition to carry out neutron transport simulations up to the coil surface. While the fast neutron flux at the coil surface is small indicating sufficient shielding, the irregular shape and large excursions of the preliminary coil set motivate us to continue to search for alternative coil sets. In that context, this result should be considered a demonstration of the workflow rather than a final design. In fact, the developed workflow will make it possible to optimize the design further to address the issues described above.

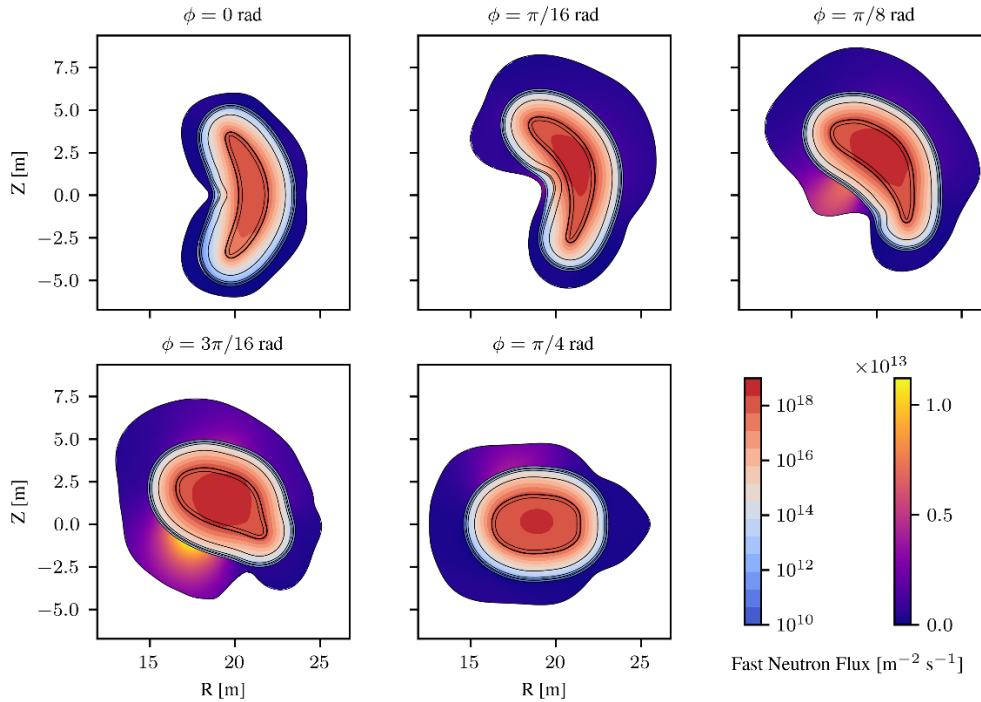


Figure 3: Poloidal cuts of neutron transport simulations up to the coil surface for a new stellarator configuration.

4. PARAMETRIC MULTI-PHYSICS WORKFLOW FOR STELLARATOR MAGNET DESIGN

Designing magnetic coils for stellarators presents a unique challenge due to their complex, non-planar 3D geometries. To address this, a parametric, multi-physics workflow has been developed [11], enabling efficient pre-dimensioning of high-field stellarator magnet systems. The tool chain is designed to be applicable to a range of stellarator configurations using only the central coil filament and current specifications as input.

The workflow involves:

- Electromagnetic analysis, to evaluate the magnetic field distribution and Lorentz forces;
- Mechanical analysis, to assess stresses and strains in the coil and support structure under operational loads;
- Thermal-hydraulic analysis, to verify temperature margins during steady-state operation and ensure safe behavior during quench events.

The methodology has been applied to an older reactor stellarator coil set (as the new configuration and coil set was not yet available when the work started) assuming low-temperature superconducting (LTS) technology and a realistic winding pack design & cross-section with a peak magnetic fields of ~ 12 T [12]. The electromagnetic model, based on finite element analysis, computes the magnetic field distribution, confirms target field values on the plasma axis, and evaluates Lorentz forces. Stored energy for the full 50-coil system is around 160 GJ, with excellent agreement (within 1.5%) between ANSYS and benchmarked tools such as Opera3D and MATLAB.

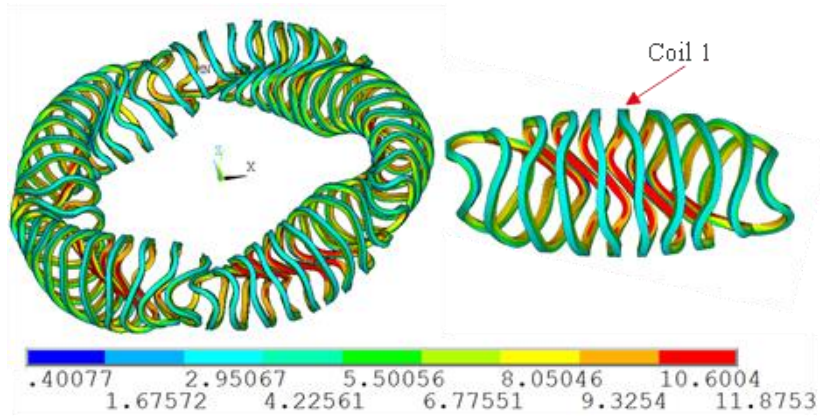


Figure 4: Electromagnetic analysis of an older stellarator coil set showing the peak field on the inboard side where coils touch.

Mechanically, the workflow assesses stress and strain in the winding pack and support structure, using a homogenized material approach to balance fidelity and computational efficiency. The analysis simulates cooldown and Lorentz-force loading at 4.2 K. Stress levels remain below material limits in most regions, with peak values occurring at localized geometric transitions as is typical the case in stellarators. All calculated strain values remain within the reversible regime for Nb_3Sn , ensuring superconducting performance is preserved.

Thermal-hydraulic simulations (using THEA) validate both steady-state operation and quench response. With an effective magnetic field of up to ~ 12 T, all locations along the conductor maintain a temperature margin above 1.5 K—meeting DEMO design criteria. Quench simulations confirm that hotspot temperatures remain well below critical limits (250 K for superconductor and 150 K for jacket), even under conservative assumptions. These results suggest design margins can be optimized in future iterations to reduce material usage or increase performance.

This workflow represents a significant step toward integrating physics and engineering in stellarator development. It enables rapid evaluation and comparison of magnetic configurations and provides essential feedback for plasma optimization and reactor-relevant design. Future efforts will extend the framework to high-temperature superconductors (HTS) and explore alternative stellarator configurations and coil sets.

5. OTHER ACTIVITIES

Apart from the work dedicated to automated design tools, also more detailed technical work is carried out within EUROfusion SPPS. One fundamental aspect involves the question of how existing blanket concepts can be adopted to stellarator geometry and which challenges arise during the process. This process is studied using as example the Dual Coolant Liquid Lead breeding blanket (DCLL) concept focusing on integration issues [13, 14] such as:

- Blanket segmentation
- Remote Maintenance handling
- First Wall designs

A liquid metal concept such as the DCLL additionally requires the consideration of magnetohydrodynamic effects. Consequently, 3D simulations of metal flows in a non-uniform magnetic field have started including the impact of partial insulations.

Finally, a multi-scale approach is under development for the thermo-mechanical behaviour of the blanket in stellarator geometry using neutron heating from neutronics simulations as input. The procedure uses models of different complexity. By coupling coarse and refined models iteratively, it enables focused analysis of critical regions using accurate boundary conditions from larger-scale simulations. This strategy ensures reliable results while significantly reducing computational cost and modelling effort.

6. CONCLUSIONS

The development of a viable stellarator-based fusion power plant requires tight integration of physics and engineering, alongside novel computational tools capable of handling complex 3D geometries. Within the EUROfusion Stellarator Power Plant Studies (SPPS), significant progress has been made in establishing such a design workflow. Key achievements include the creation of parametric geometry tools, the implementation of a deterministic neutronics code compatible with high-fidelity meshed geometries, and the development of a parametric multi-physics workflow for stellarator magnet systems. Furthermore, a number of more detailed technical investigations are ongoing like the adoption of the DCCL blanket concept to stellarators, corresponding MHD and thermohydraulic analysis, remote maintenance considerations, etc.

Together, the tools presented here enable the rapid iteration from the magnetic configuration to reactor component evaluation, including blanket geometry, neutron shielding, coil design, and thermo-mechanical performance. The application of this workflow to an optimized quasi-isodynamic configuration demonstrates both its flexibility and its potential to guide future reactor design.

Looking ahead, the presented toolchain provides a foundation for comprehensive design-space exploration and optimization of stellarator reactors. Future efforts will focus on improving component integration, exploring advanced superconducting technologies, and refining candidate configurations for reactor-scale application.

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