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Overview of European efforts and advances in Stellarator power plant studies

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ABSTRACT

The stellarator concept is a promising candidate for a steady-state fusion power plant, but currently lacking behind the tokamak developments. In order to bring the stellarator concept to maturity, a new EUROfusion Task has been established within the Work Package Prospective Research & Development (WP-PRD) called Stellarator Power Plant Studies (SPPS). This task addresses the stellarator-specific engineering aspects relevant on the way to a fusion reactor. This paper reports on the strategy of this task and provides an overview over ongoing activities as well as initial achievements.

1. Introduction

To achieve controlled nuclear fusion for virtually inexhaustible energy generation is an ambition that unites the fusion community. So far the main workhorse to realise this ambition has been the tokamak concept, which consequently resulted in the construction of the ITER project and logically, based on the ITER experience, the design of a demonstration fusion power plant: DEMO.

However, there is an alternative: the stellarator. The stellarator concept has recently gained substantial attention, in particular due to the success of the Wendelstein 7-X experiment — an optimised stellarator located in Greifswald, Germany [2]. In contrast to its axisymmetric cousin, the stellarator intrinsically offers steady-state operation and is inherently easier to operate due to the absence of disruptions and current-related instabilities.

A prudent attempt to de-risk the success of fusion energy must include the parallel development of the promising stellarator concept. This has also been recognised by the EUROfusion consortium and in 2021, within the Work Package of Prospective Research & Development (WP-PRD), a Task was dedicated to this activity called Stellarator Power Plant Studies (SPPS).

While overdue, this activity comes at a time where also large progress in stellarator physics is reported. In particular, stellarator theory has made tremendous progress in the recent years. A worldwide effort resulted in new approaches to generate stellarator magnetic configurations with unprecedented physics performance. This resulted, for example, in new configurations with excellent fast particle confinement [3] — a historical weakness of stellarators. Simultaneously, the historically high neoclassical transport losses in stellarators can be suppressed by appropriate shaping of the magnetic configuration — which was demonstrated experimentally [4] by the Wendelstien 7-X (W7-X) stellarator experiment. Consequently, and similar to tokamaks, turbulence losses dominate the core plasma and its suppression has become an active area of research. But also here, the newly found understanding helps to optimise stellarator magnetic fields such that they inhibit turbulence simply be design [5], an avenue unavailable to tokamaks.

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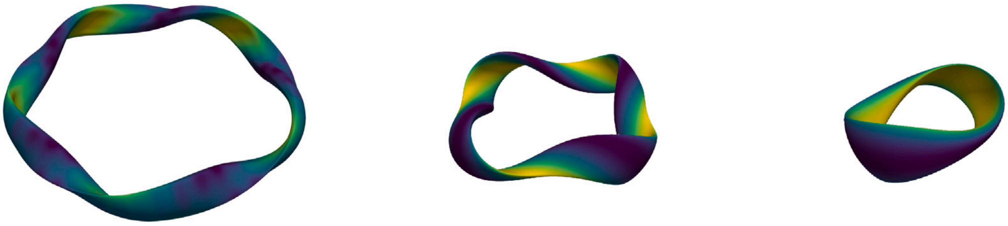

Fig. 1. Examples of stellarator magnetic configurations with different symmetries, from left to right: quasi-isodnyamic, quasi-helical symmetric, and quasi-axisymmetric [1].

This excitement has also reached the private sector and several stellarator fusion startups have been founded in Europe and around the world. In fact, the number of stellarator startups rivals the number of tokamak startups in the private sector, each represented by 6 at the moment [6].

A gap that currently exists in stellarator research and that likely also applies to the private sector, is the better integration of physics and engineering considerations in order to obtain a complete and holistic design of next-step stellarator device. For example, a clear gap exists in the stellarator community for the assessment and optimisation of divertors — a component where physics and engineering meets. Only one single tool exists that can currently sufficiently simulate the 3D stellarator edge layer, with only a handful users worldwide and even less developers. Such bottlenecks can hinder the progress in developing a reactor-scale stellarator.

Apart from the gap in integration, there is also a large research gap on the engineering side, specifically. In fact, very little research has been done on stellarator engineering over the last decades. A fusion-grade reactor is substantially different from today's experiments. A reactor needs to endure harsh environments and a continuous heavy stream of highly energetic neutrons. Consequently, the neutronic assessment of any next-step device is of high priority as well as the regular replacement of the degraded in-vessel components in a nuclear environment, requiring a well thought out remote maintenance concept from the beginning. This is highly interlinked with the coil shapes that define the availabe space for port access. There are, of course, many more engineering considerations for a reactor scale stellarator: e.g. higher B-fields are leading to large electromagnetic forces and stress in the support structure as well as higher superconductor strain; the thermal field from neutron energy deposition causes thermal expansion, displacement, and stress; to name only a few examples of topics that need to be addressed.

But it is here that SPPS comes into play, which has the goal and mandate to address these aspects and prepare the stellarator concept for its next step. This paper aims to provide an overview over the initial activities of this task, highlighting the strategy followed in SPPS and celebrating first achievements. Consequently, the description is from a high-level birds eye view and the reader is referred to individual papers and reference cited throughout this work for more details.

The structure of the article is as follows: First, the objectives and strategy of SPPS are discussed in Section 2, which is followed by an update on stellarator systems studies and modelling in Section 3. Next, the progress in stellarator neutronics is highlighted in Section 4 followed by some examples of parametric modelling in Section 5. Finally, a first look at possible remote maintenance schemes is presented in Section 6 and several recently started activities are briefly mentioned in Section 7. The work is concluded by a short summary in Section 8.

2. Objectives & strategy of SPPS

2.1. Objectives

The objective of SPPS is straightforward and as formulated by the EUROfusion roadmap is to **bring the stellarator concept to maturity** [7].

This formulation implies that the stellarator concept is currently in an immature state. The simple reason being that the stellarator is about one generation behind the tokamak with far fewer experimental devices in operation and consequently a less explored physics basis. The stellarator concept, however, made large steps forwards in the recent years, both in terms of theoretical and experimental understanding. Experimentally, the prototype Wendelstein 7-X stellarator has demonstrated quasi-steady operation for 10min [8], stable detachment with an island divertor configuration [9], and record stellarator 'Triple-product' [10], among other achievements. On the theoretical side, stellarator optimisation has gained strong momentum demonstrating new configurations with excellent fast particle confinement [3] and even turbulence reduction [5], a big step towards solving the remaining physics challenges of the stellarator concept. One can thus argue that, on the physics front, the stellarator is catching up with the tokamak concept rapidly, which is frequently acknowledged in the community.

However, what has been missing so far are significant engineering aspects, such as the 3D blanket design or an optimised divertor geometry among others, that need to be addressed in order to achieve a stellarator reactor concept [11]. And this, precisely, is the focus of SPPS, which aims to identify the key stellarator-specific design drivers and engineering issues and address them in parallel to the physics progress. SPPS thus aims to:

1. rapidly catch up with the tokamak DEMO engineering developments
2. demonstrate the engineering viability of the stellarator concept
3. deliver attractive options for a next-step stellarator device

Given that the work of SPPS started only in 2021 and that the stellarator reactor studies are in the early pre-conceptual design phase means that, compared to the tokamak DEMO, our team can be more open-minded to new and emerging technologies and the benefit they would bring to stellarator design. High temperature superconductors, liquid metal divertors/blankets, are just some of the examples that can be considered in parallel to the established technologies.

In addition, stellarator design studies should consider systems engineering aspects and an integrated systems view of physics, engineering, and economics aspects from the beginning. Fusion research is a multidisciplinary endeavour with competing subsystems and constraints. An early emphasis on integration is therefore highly beneficial to avoid costly design iterations later in the life-cycle.

Finally, on the one hand the stellarator community is much smaller than the tokamak community (without a long standing tradition of engineering studies), and on the other hand the complex 3D geometry makes most of the tasks more challenging. Consequently, a major goal of SPPS is to leverage the small existing stellarator expertise in the EU to develop more competences and train a new generation of young stellarator enthusiasts that will push stellarator engineering forward.

In order to realise this set of ambitious goals with, frankly, quite limited resources, requires a clear and focused strategy, which will be discussed in the next subsection.

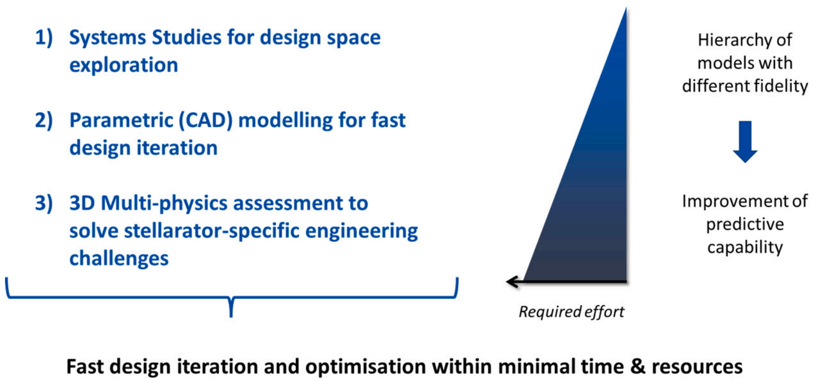

Fig. 2. High-level illustration of the SPPS strategy providing a cascade in model fidelity to scope the design space and assess promising design points in more detail with the help of parametric modelling — ultimately achieving fast design iterations within minimal time and resources.

2.2. Strategy

The earliest reactor studies accompanied the W7-X design and were consequently a straightforward and linear extrapolation of W7-X to reactor size, thereby considerably simplifying reactor design [12,13]. However, this has changed dramatically and, as mentioned earlier, stellarator optimisation has made significant progress in the recent years leading to new stellarator magnetic configurations with enhanced physics properties like substantially improved fast particle confinement or turbulence optimisation. This success can also be attributed to the development and progress in optimisation tools (e.g. STELLOPT [14], SIMSOPT [15], etc.) and their widespread application and new capabilities. However, stellarator optimisation cannot be considered complete yet as reactor-relevant engineering aspects are largely absent.

For SPPS and the engineering studies, this has the consequence that we must remain open to a variety of vastly different stellarator shapes and even anticipate the development of new magnetic configurations in the future. Furthermore, SPPS should provide the critical engineering expertise and respective models for reactor-relevant stellarator optimisation. The substantial difference in stellarator configurations is illustrated in Fig. 1 for three examples.

An established method to investigate such a vast design space is the use of so-called systems codes. Systems codes are a comprehensive framework to model an entire fusion power plant. Each subsystem can, in a modular way, be described by its own models allowing an easy adaption of new physics or engineering developments. The combination of physics, engineering, and economic considerations makes the framework intrinsically multidisciplinary. Generally, the models in a systems code have a lower fidelity, sacrificing some accuracy for an overall speedup which enables rapid scans of the design space.

This is an ideal tool for stellarators and builds the first pillar of the SPPS strategy, as new configurations obtained through stellarator optimisation can be quickly assessed for their engineering and economic feasibility and potential promising candidates quickly selected for more detailed investigations. The recent activities for stellarator systems code developments will be explained in Section 3.

If a promising configuration is found, a more detailed engineering and multi-physics assessment is required, consisting of e.g. neutronics, electro-magnetics, thermo-hydraulics, structural, remote maintenance etc. This is the third pillar of the SPPS strategy and requires high fidelity modelling, and aims to identify (and solve) general stellarator-specific engineering challenges that need special attention. In this paper, neutronics and its challanges in stellarator geometry stands exemplary for this pillar and are discussed in Section 4.

However, the high-fidelity models rely on a 3D CAD model (or something equivalent) as input. To bridge the gap between the systems studies and multi-physics modelling, an intermediate step is required. This step builds the second pillar of the SPPS strategy and is focused on parametric (CAD) modelling. In practice this mean the development of tools that start from e.g. a 3D stellarator magnetic configuration and then produce automatically CAD (or equivalent) models of e.g. 3D blanket layers, finite coils, etc. that can be directly imported into the high fidelity multi-physics codes. Examples of work that contributes to this pillar are given in Section 5.

This initial workflow provides a cascade of low to high fidelity for a selection of promising stellarator candidate configurations and **enables fast design iterations and optimisation within minimal time and resources** in the pre-conceptual phase, illustrated in Fig. 2.

However, before this strategy and worflow can be fully exploited, the associated tools and software needs to be developed for the stellarator concept. Experience has shown that established tokamak tools can often not be used due to their hard implementation of axisymmetry. The progress of current developments will be discussed in the following sections.

3. Systems code

Systems codes are optimal tools for design space exploration. The most established systems code in Europe is called *PROCESS* [16,17], which has grown over decades and has been extensively used for the tokamak DEMO [18] and STEP [19] conceptual design. In 2014, the first stellarator-specific models were developed and implemented in PROCESS [20–22]. These early models, however, were specific to the 5-periodic W7-X line and had little flexibility. With the emergence of various new promising stellarator configurations, it became apparent that these models needed an overhaul and generalisation that allowed to model any type of stellarator.

As we started the development of a new generation of models we realised that a number of calculations needed a full 3D treatment in order to provide accurate enough results for generic stellarator configurations. An example, that will be discussed explicitly below in Section 3.1, is the calculation of the maximum field on the coil which determines the current density that can be obtained for a selected superconductor and the resulting coil size. Although such calculations can be done quite fast, they are not fast enough for the optimisation procedure of PROCESS which aims to operate on a seconds time scale. We therefore introduced a new *pre-processing* step for the stellarator version that takes a generic stellarator magnetic configuration and coil filaments as input (from stellarator optimisation). It then pre-calculates effective parameters that can be used in PROCESS, reducing the dimensionality while retaining the full 3D information and accuracy [23,24]. The new workflow is illustrated in Fig. 3.

Apart from the magnet system, new engineering models are being developed, such as for the 3D stellarator blanket based on deterministic neutronics [25] as well as more detailed models for the divertor.

In the future, we also aspire to close the optimisation loop as indicated in the worflow. I.e. a new stellarator magnetic configuration

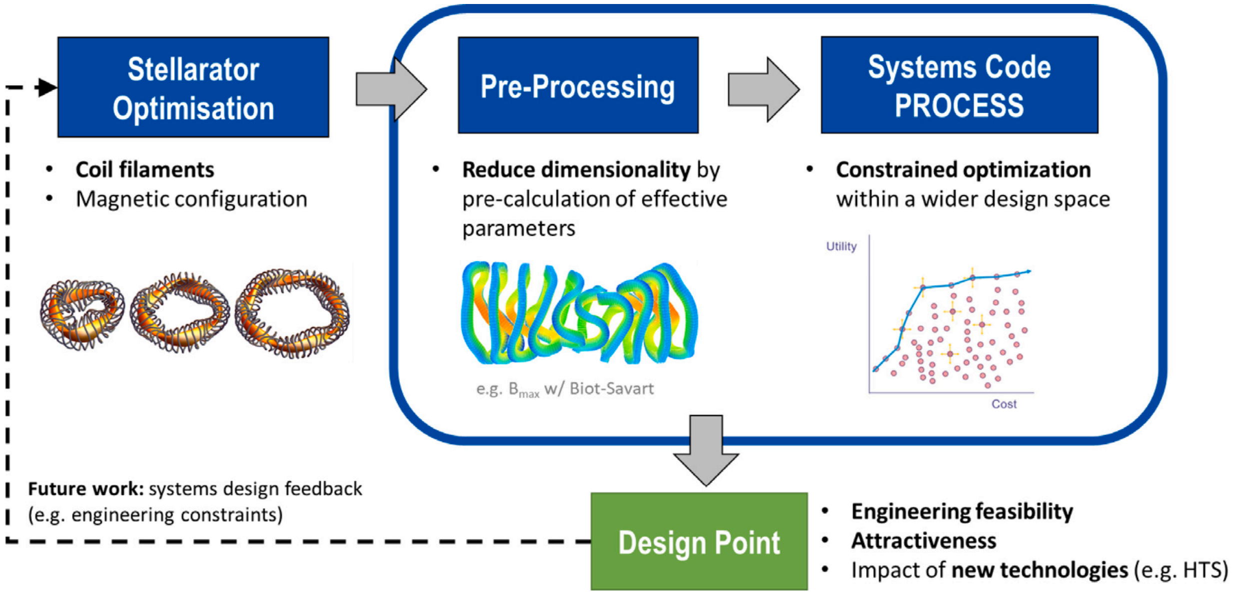

Fig. 3. Illustration of the current worflow for the fast engineering feasibility assessment of new stellarator magnetic configurations using the systems code PROCESS including a new stellarator-specific pre-processing step. Also indicated is the planned closure of the feedback loop to provide input to stellarator optimisation.

could be checked within the systems code framework for its engineering feasibility and the result could directly couple back to stellarator optimisation to improve the configuration based on engineering feedback. Alternatively, it is also conceivable that the engineering models that we develop can be directly implemented into stellarator optimisation frameworks to reach a combined physics and engineering optimisation.

3.1. Example: Magnet system model

The development of appropriate stellarator engineering models is an intellectual challenge that requires new innovate approaches. A quite promising model has been developed over the past years for the magnet system which will be briefly discussed here [23,24].

The maximum current density j_{crit} that a superconductor can withstand depends on the strength of the surrounding magnetic flux density. The limiting factor for a coil or the entire magnet system thereof is the maximum B-field inside the winding pack of any coil B_{max}. This is straightforward to estimate for the inboard side of a tokamak but not for stellarators. Due to the complex 3D shape of the coils, generally a full 5D Biot–Savart simulation would be required of the entire magnet system to identify B_{max}, which is computationally expensive.

For the systems code purpose, a new method was developed which discretises coils in a set of $\mathcal{O}(100)$ cuboid elements. Since there exists an analytic solution to Biot–Savarts equation for cuboid elements with constant current density, B_{max} can be quickly calculated by summing over all elements. By iteration, the dimension of the winding pack and current density can then be self-consistently derived for a given superconductor parametrisation and any generic 3D coil filaments.

In addition, the model self-consistently adjusts the copper fraction to ensure coil integrity during a hypothetical quench following from considerations on energy conservation. Based on the final winding pack dimensions, lateral and radial forces can be straightforward calculated as well as the minimum bending radius of the conductors. The model is described in detail in [23].

Overall, the new magnet system model is capable to self-consistently calculate:

1. B_{max} and j_{crit} for any generic 3D coil set
2. the resulting winding pack dimensions based of any superconductor parametrisation
3. adjust the copper fraction for quench protection

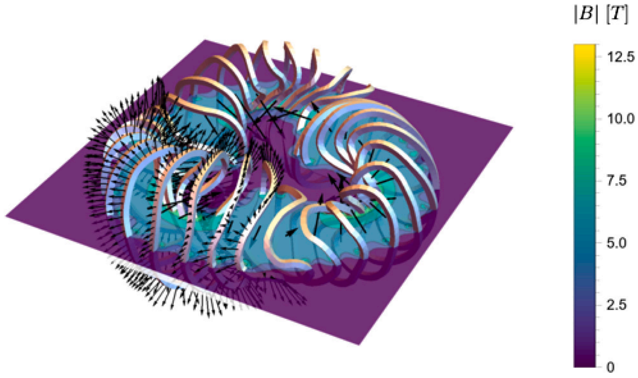

Fig. 4. Colour-coded magnetic field strength of a stellarator coil set in the horizontal plane as well as electromagnetic forces indicated by black arrows as calculated in the pre-processing step of the systems code worflow.

4. lateral and radial forces in 3D
5. the minimum bending radius of the conductors
6. coil-coil and coil-plasma distances

A corresponding result is illustrated in Fig. 4.

What is still missing in the magnet system model is the calculation of the superconductor strain, which can degrade performance and usually has strict limits. Another important factor that is still missing is the calculation of the stress in the coil casing or support structure resulting from the electromagnetic forces. While the superconductor strain is in principle straightforward to implement, the calculation of the material stress requires a concept and automatic generation of (intercoil) support structure, which is still in progress.

4. Stellarator neutronics

One of the most important aspects in the design process of a fusion power plant is the neutronic analysis. Consequently, the development and neutronics assessment of stellarator configurations is a high priority for SPPS. Furthermore, relating back to the SPPS strategy, this neutronics section also serves as an example for the work and challanges within the pillar of high fidelity multi-physics assessments.

The fusion standard for neutronics assessment is the Monte Carlo N-Particle Transport code (MCNP) [26]. However, MCNP requires a specific format for the geometry, namely constructive solid geometry (CSG). Unfortunately, the initial CAD model that was inherited by the SPPS team from the old W7-X like models [13] consisted of smooth 3D spline definitions, fundamentally incompatible with CSG. Despite this, two workflows were developed to make neutronics simulations of such geometry feasible, both relying on external software. The first included the use of the DAGMC software package that allows to perform MCNP simulations directly on the CAD model (by converting it to a mesh) [27], while the second approach relied on SuperMC to facet the original CAD model into a CSG model that can be used with MCNP [28].

While prototype simulations for both approaches were ultimately successful, they revealed significant challenges in preparing and converting the stellarator geometry to be useable within MCNP. The cumbersome conversion required time consuming manual work, was slow and with limited variability. Consequently, it was deemed unpractical by the team to continue this route.

Instead, several new workflows have been recently developed to enable an automatic and quick process for stellarator neutronics assessment. The first important step was to develop an in-house software that can automatically generate appropriate stellarator CAD models for the blanket (and coils) based of any generic magnetic configuration. Using a stellarator magnetic field as input (analytically described by Fourier coefficients), a first wall shape can be found by e.g. extending the last plasma surface using surface normals. Using an inverse Fourier transform on the resulting point cloud allows to repeat that method to generate an arbitrary number of blanket/shielding layers [29]. From these surfaces it is then straightforward to generate 3D points and any mesh at arbitrary resolution for which several tools have been developed.

A tetrahedral mesh generated this way can then be easily coupled with GEOUNED [30], which is a tool that converts complex CAD models into MNCP inputs [31,32]. Alternatively to MCNP, also the neutron transport code Serptent2 can be used which is capable to do Monte Carlo neutron transport simulations directly on the mesh [33]. Both methods were benchmarked for stellarator geometry in the frame of SPPS resulting in accurate agreement [34].

It can be summarised that new workflows have been developed for stellarators, which are capable of automatically generating CAD models based of a stellarator magnetic configuration. These can then be automatically converted or directly used in modern Monte Carlo neutron transport codes such as MCNP, Serptent2, or OpenMC.

The power of such capabilities is discussed as an example in Section 5.

4.1. Deterministic neutronics

Monte Carlo transport codes provide high fidelity, but at the cost of computational power. Sufficiently accurate simulations typically require 10^8–10^9 samples leading to several thousand CPU hours on a supercomputer. In many cases this may not even be sufficient for areas far away from the source, which then require specific local weight window techniques.

For early scoping studies (e.g. within a systems code) or blanket optimisation, faster models could be useful. Consequently, in parallel to the high fidelity Monte Carlo tools, some research has been dedicated to develop deterministic methods for stellarators. In this context a Matrix method was derived, which essentially splits the source in a number of point sources and the first wall in small elements. It is then straightforward to calculate the neutron flux on any wall element by the inverse square law by summation over each source point. This way, the Neutron Wall Load (NWL) in a stellarator can be calculated for any generic geometry within one second computational time. While this method does not include the neutron transport in the blanket, it is still useful for e.g. optimising the First Wall shape to homogeneously distribute neutrons to increase life time by reducing peak loads as explained in [29] and here illustrated by Fig. 5. A degree of freedom in design inaccessible to tokamaks. An analysis of how this would affect the tritium breeding ratio (TBR) is ongoing [35].

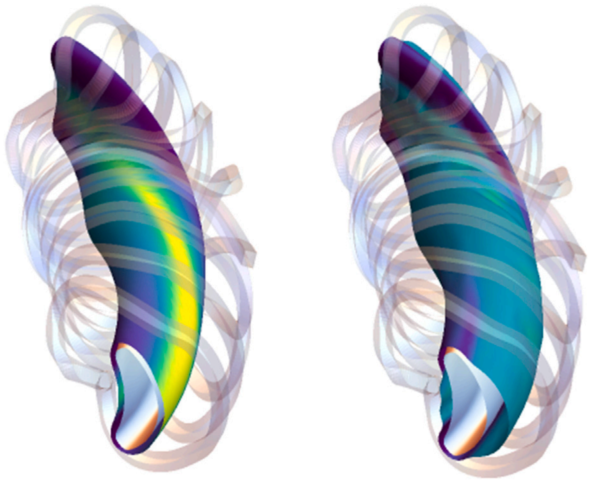

Fig. 5. Use of a deterministic matrix method for the optimisation of the first wall shape of a stellarator aiming to reduce peak neutron loads. Left: Colour-coded neutron flux (yellow: high, green: medium, blue: low) for a first wall that follows the plasma shape with a clearly seen stripe of peak neutron load. Right: An optimised first wall that succeeds in reducing the peak loads. Note the increased plasma-wall distance.

In order to extend such a method to the full blanket and neutron transport within it, currently a fully deterministic neutron method is under development for stellarators [25].

5. Examples for parametric modelling

As mentioned in Section 2.2, one of the pillars of the SPPS strategy is the development of intermediary tools that can generate parametric CAD models or equivalent formats to provide input for the high fidelity multi-physics codes. In the following, two brief examples of such applications are presented.

5.1. Example 1: Blanket layers

An important milestone in advancing the stellarator design and analysis has been the development of tools that can generate a meshed model of blanket/shielding layers starting from an arbitrary stellarator magnetic configuration. The generality of such an approach can be exploited to add further degrees of freedom for parametric modelling. For example, it is straightforward to parametrically change the thickness of the breeder or shielding layers and investigate the impact this would have on the TBR or shielding. To demonstrate the power of this approach, this precise example is shown in Fig. 6, where each point corresponds to a full 3D stellarator neutronics simulation generated by the new parametric workflow as discussed above [29,31–34]. It should be noted that such an achievement was only possible due to the combined efforts and expertise of the entire SPPS team, each contributing their specific experience to overcome the encountered challenges.

But even more generally, as discussed in 4.1 the entire 3D shape of the first wall and blanket can be parametrically changed, for example to reduce peak heat loads or simplify the blanket geometry within a stellarator.

5.2. Example 2: Number of coils

Another example of parametric modelling is the variation of the number of coils as illustrated in Fig. 7. For example, it could be

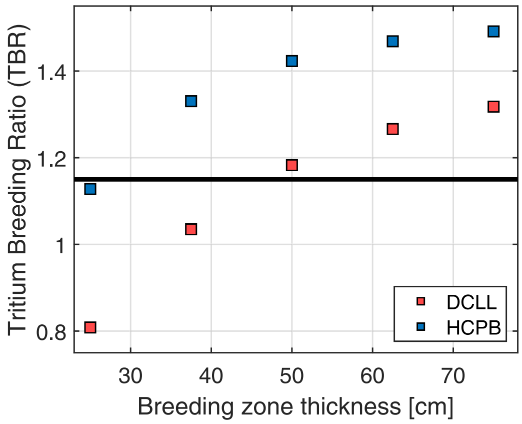

Fig. 6. Parametric variation of the (homogenised) breeding zone thickness in full 3D stellarator geometry for an Helium Cooled Pebble Bed (HCPB) and Dual Cooled Liquid Lead (DCLL) like blanket concept and the impact on the tritium breeding ratio (TBR).

desirable to decrease the number of coils to have more space between coils for remote maintenance aspects. However, a reduction of coils will decrease the desired magnetic field accuracy and leads to larger winding packs. Such parametric studies can therefore be useful to determine the optimal number of coils as a compromise between minimising cost, maximising field accuracy, and maximising port space.

6. Remote maintenance

Apart from neutronics, but strongly related, remote maintenance also plays an important role in the conceptual outline of any fusion power plant. The in-vessel components like the blanket and divertor have to endure a continuous stream of highly energetic neutrons. This neutron flux continuously displaces atoms inside the material causing damage that accumulates over time, degrading the material and thus limiting its lifetime. Therefore, from the beginning of the design procedure, a strategy must be in place that ensures that these components can be regularly exchanged via remote handling/maintenance.

Stellarators typically have more coils than a tokamak and as a consequence, stellarators feature less space between coils resulting in comparatively smaller ports. The ease of remote maintenance scales with the size of the available port. The larger the port, the larger can be individual blanket segments and the more contingency is available for movement. Consequently, smaller ports would lead to many more and much smaller blanket segmentation, which could drastically increase maintenance time and complexity. Moreover, the 3D shaping of stellarators could require more complex movement to extract blanket elements requiring potentially more space and more flexible RM equipment.

So far, no established maintenance concept exists for stellarators despite its importance. To start an investigation into stellarator remote maintenance, as an initial first step, four different remote maintenance approaches were discussed and qualitatively compared against each other. The four approaches are:

1. The baseline (A1) approach is inspired by the tokamak DEMO developments and considers only vertical ports and vertical handling of all blanket segments.
2. The second approach (A2) is an extension of the vertical maintenance concept by using the outboard space between coils to add substantial horizontal ports for a hybrid maintenance.
3. Similarly, approach three (A3) is an extension of (A1) by trying to enlarge the vertical ports. The conceptual idea assumes that one coil per module could be designed larger than the rest and be moved toroidally during maintenance to allow a significantly larger vertical port.

Table 1
Qualitative comparison of four different remote maintenance approaches for stellarator power plants.

Consideration	Approach 1	Approach 2	Approach 3	Approach 4
Blanket handling	0	+1	+1	+2
Divertor handling	0	−1	0	+1
Failure scenarios	0	+1	+1	+1
Inspectability	0	+1	+1	+1
Hardware costs	0	0	0	−2
Radiation	0	−1	−1	−1
Wider plan implications	0	−1	+1	0
Total:	0	0	+1	0

4. Finally, the fourth approach (A4) is conceptually different as it assumes that an entire module of the stellarator could be split and moved radially to allow a large open space from the side.

It is clear that each of these approaches has substantial implications on the remote maintenance scheme. In a preliminary attempt to assess the capability of the four approaches, we opted for a relative comparison between them for a number of criteria such as: blanket handling, divertor handling, etc. (full list in Table 1). In this relative comparison, approach 1 served as reference point. Then for each category, it was assessed if the other approaches provide an advantage or disadvantage, i.e. longer maintenance time, more complex equipment, etc. Based on this qualitative assessment, a score was given between −2 and +2, where −2 means the approach is much worse than the reference, and +2 means the approach is much better than the reference. For a detailed discussion the reader is referred to corresponding EUROfusion report [36]. Given the preliminary state of remote maintenance in stellarators and the overview character of this paper, only the qualitative result shall be briefly discussed here based on the scoring matrix as illustrated in Table 1.

Adding horizontal ports (A2) may alleviate the blanket handling and ease inspectibility, but such additional ports would need additional radiation protection structures during maintenance complicating the wider plant layout.

The shift of a larger coil to obtain a much larger vertical port (A3) would quite substantially help with vertical maintenance and inspection. However, normal-to-superconducting joints of a magnet is one of the most sensitive parts of a fusion reactor. Disconnecting such a coil, as well as from the helium cooling circuits, can be considered a quite difficult endeavour impacting the wider plant infrastructure.

Finally, to split off an entire stellarator module (A4) would guarantee the most space for blanket and divertor handling as well as inspection. However, disconnecting and transporting an entire sector seems challenging requiring a specific plant layout and hardware. Furthermore, additional efforts would be necessary to isolate the segments to guarantee radiation safety during maintenance.

The unfortunate result of this qualitative analysis is that within a discussion margin of ±1 all approaches achieve the same total score. This means that, at least for the discussed concepts, there is no golden bullet and advantages in one category usually come at the cost of a disadvantage in another.

Separately, a study has also been performed to assess if an ITER-like or DEMO-like rail-based handling system could be beneficial for stellarators [37]. Due to the size and mass of blanket segments an ITER-like approach would be unfeasible. A DEMO-like rail system seems more applicable, but the 3D geometry would substantially complicate the rail path, which again emphasises the need to include remote maintenance considerations from the beginning.

Ultimately, the maintenance concept and this analysis will also depend on the specific choice of the blanket type. At this moment it is not clear which blanket concept is the most suited for a stellarator. To arrive at such a conclusion requires a detailed assessment of each concept within stellarator geometry. As a first step, the analysis of the

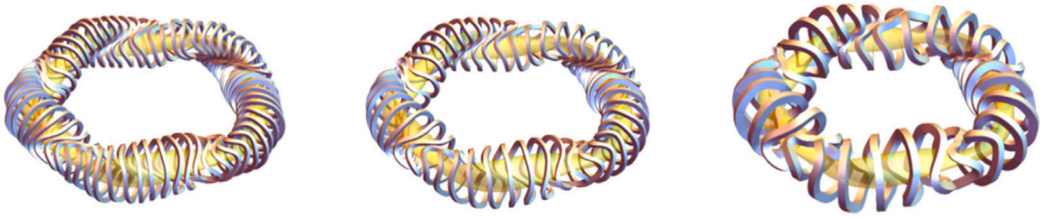

Fig. 7. Demonstration of the impact of the number of coils on the coil dimensions for a 5-field period stellarator.

DCLL blanket type has been started [31,38], where in addition to remote maintenance aspects also the orientation of the liquid metal flow relative to the magnetic field plays a role as magnetohydrodynamic (MHD) forces can lead to excessive pressure drop.

7. Activities in progress

Given the limited resources and team, not all aspects relevant for a stellarator fusion power plant can be sufficiently addressed yet. However, some additional activities were recently started that are briefly mentioned below.

7.1. Divertor target optimisation

The divertor responsible for energy and particle exhaust is an integral component of any fusion plant. It is an highly integrated component that requires a careful selection of materials and design, needs remote maintenance, and the maximum allowable heat load could limit the size of the entire device.

The leading divertor concept for stellarators at the moment is the island divertor as employed in the W7-X experiment, where target plates intersect fixed magnetic islands at the plasma edge. This concept has been performing so far exceedingly well in W7-X experiments demonstrating good energy exhaust and stable long-term detachment with vanishing heat loads [9]. Experiments at higher heating power are eagerly awaited to confirm that this performance holds for higher power densities. However, the W7-X divertor was designed to accommodate the configuration flexibility of the experiment and as a consequence features quite open divertor geometry. It is apparent that any open divertor geometry will have difficulties in handling particle exhaust and achieving sufficient neutral compression for pumping [39]. It is therefore prudent to explore alternative target geometries for stellarator island divertors that are more closed and can reflect neutral particles to the pumping space. Even a dome structure as considered for tokamaks could be conceivable.

Simultaneously, or more generally, we have to assess the divertor heat load in new stellarator configurations and minimise the peak loads by maximising the strike line footprint. We aim to achieve this by building up a framework that is capable of 3D divertor target shape optimisation in stellarator geometry. In a second step, it is also conceivable to extend this by optimising coil currents to manipulate the island topology. A task for divertor shape optimisation has been started.

7.2. Electro-magnetics & winding pack design

As already mentioned in 3.1, an electromagnetic analysis of the 3D stellarator magnet system is important to both design the layout of the winding pack as well as the support structure. Systems code can provide a rough first estimate, but ultimately more detailed simulations are required that model a proposed conductor layout as well as dimension the coil casing and intercoil support structure to accommodate elctromagnetic forces. Similar to the other workflows, the tools require a flexible parametrisation to allow for fast design iterations and assessment. The development of the respective tools and workflow has been initiated [40].

7.3. Thermo-mechanics

Apart from electromagnetic forces, also thermal expansion through e.g. thermal loads caused by neutron absorption in the blanket will cause mechanical stress in the components and macroscopic displacements. The modelling of such effects is quite complex, in particular in stellarator geometry as both a detailed heterogeneous model of the blanket is required as well as an accurate thermal field [41,42]. An activity to develop an appropriate modelling approach has been started, combining the detailed modelling of a small heterogeneous section with a larger homogenised model in an hybrid approach.

8. Conclusions and outlook

In acknowledgement of the success of the Wendelstein 7-X stellarator experiment and recent progress in stellarator theory understanding and optimisation, a new EUROfusion Task for Stellarator Power Plant Studies (SPPS) has been started in 2021. This task addresses the stellarator-specific engineering challenges on the way to a stellarator fusion power plant. The aim is catch up with the tokamak DEMO developments and provide attractive options for a next-step stellarator device.

However, the advancement in stellarator physics has lead to various new magnetic configurations that have vastly different 3D geometries and it is not yet clear which stellarator shape may ultimately be superior and selected. That means that SPPS activities and modelling need to be capable of handling new and emerging stellarator geometries. To enable this, a research strategy was developed that combines high level systems code modelling for design space exploration with the generation of parametric CAD models for the detailed assessment with high fidelity codes for selected design points. Combined, this strategy will allow fast design iterations within minimal time and resources.

This approach has already proven to be highly effective as challenges in stellarator neutronics modelling could be overcome by introducing parametric, meshed CAD blanket models that can be easily converted to MCNP inputs or used directly in Serpent2 or OpenMC. This capability is a first key milestone for SPPS. In parallel, innovative activities have been started on deterministic neutronics that can e.g. be used in systems codes or for shape optimisation of the first wall to reduce neutron peak loads.

Generally, a new generation of systems code models is under development that can handle any generic type of stellarator geometry, allowing to test new magnetic configurations quickly for their engineering feasibility. Ultimately, we aim to close this optimisation loop by providing feedback to the physics based stellarator optimisation framework.

Systems code, however, are (so far) blind to remote maintenance, which is a key design driver of any fusion power plant, but requires a more detailed expert assessment. Four different approaches (vertical ports only, vertical & horizontal ports, enlarged vertical ports, and sector splitting) were qualitatively compared according to different design criteria. It turns out that advantages in one category lead to disadvantages in another meaning that on this qualitative level none of the concepts seemed superior. A more detailed assessment for each blanket concept seems necessary.

Apart from these major results, activities have been also started on divertor target optimisation, detailed electro-magnetic analysis and winding pack design as well as thermo-mechanical assessments.

In summary, it can be stated that SPPS has been successfully started despite the 3D geometry challenges that are faced by the team in nearly every aspect. At the moment the SPPS team is a small community and consequently training of PhDs and PostDocs is essential to bring in new talents. This needs to be accompanied by a growth in resources to be able to keep talents in the team and grow the scope of SPPS to address all relevant engineering challenges.

The current EUROfusion roadmap foresees that SPPS at the current level of funding (3-4ppy/y) will exist at least until the end of the current framework programme in 2025. Generally, a revision and update of the EUROfusion roadmap is currently in progress with an expected stronger commitment to the stellarator concept. An increase in activities in SPPS beyond 2025 seems therefore imaginable depending on the allocated resources.

CRediT authorship contribution statement

Felix Warmer: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **J. Alguacil:** Investigation, Methodology, Software. **D. Biek:** Investigation, Methodology, Software. **T. Bogaarts:** Investigation, Methodology, Software. **G. Bongiovì:** Investigation, Methodology, Software. **V. Bykov:** Investigation, Methodology, Software. **J.P. Catalán:** Investigation, Methodology, Software. **R.K. Duligal:** Investigation, Methodology, Software. **I. Fernández-Berceruelo:** Investigation, Methodology, Software. **S. Giambrone:** Investigation, Methodology, Software. **C. Hume:** Investigation, Methodology, Software. **M. Hrecinuc:** Investigation, Methodology, Software. **R. Kembleton:** Project administration, Resources. **J. Lion:** Investigation, Methodology, Software. **T. Lyytinen:** Investigation, Methodology, Software. **J.A. Noguerón Valiente:** Investigation, Methodology, Software. **I. Palermo:** Investigation, Methodology, Software. **V. Queral:** Investigation, Methodology, Software. **D. Rapisarda:** Investigation, Methodology, Software. **W.J. Rutten:** Investigation, Methodology, Software. **L. Sanchis:** Investigation, Methodology, Software. **X. Sarasola:** Investigation, Methodology, Software. **K. Sedlak:** Investigation, Methodology, Software. **A. Snicker:** Investigation, Methodology, Software. **D. Sosa:** Investigation, Methodology, Software. **F.R. Urgorri:** Investigation, Methodology, Software.

Declaration of competing interest

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Data availability

Data will be made available on request.

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