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Integrated Concept Development of Next-Step Helical-Axis Advanced Stellarators

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Abstract:
This work elaborates on the recent developments of the advanced stellartor line towards consistent next-step designs using an systemic integrated modelling approach. This means, a stellarator fusion power plant is treated as a complete system combining physics and engineering aspects employing respective tools such as transport simulations and systems codes. Care is thereby taken to consider the interactions and interplay between the different aspects and components in order to develop a consistent design entity.

1 Introduction

One of the high-level missions of the European Roadmap for the realisation of fusion energy is to bring the helical-axis advanced stellarator line (HELIAS) to maturity [1]. The near-term focus is the scientific exploitation of the Wendelstein 7-X experiment in order to assess *stellarator optimisation* in view of economic operation of a stellarator fusion power plant. After a decade of construction, W7-X successfully started operation in 2015 and will undergo upgrades in the next few years to allow steady-state operation [2].

In addition, the understanding of the physics and technology of stellarators has made significant progress in recent years. However, even with the achieved progress and assuming that stellarator optimisation can be verified in the coming years of W7-X operation it is not straightforward to extrapolate the current knowledge to a HELIAS fusion power plant. Even the conceptual design of a power-plant-like fusion device is a complex and demanding task. In the past, stellarator reactor studies considered only individual design points with focus on engineering aspects. While these studies are important for the investigated aspects, many physics aspects were treated only superficially. Moreover, due to the focus on individual designs, it is not possible to obtain a broader overview in particular with respect to parameter variations and uncertainties.

In order to overcome these drawbacks, this work goes a different, more systematic way, where not only specific aspects of next-step stellarator devices are examined, but rather they are treated as a complete system. Consequently, concepts of next-step stellarator systems are developed in an integrated manner, i.e. consistently combining physics, engineering and economic considerations, in order to produce conceptual designs and assess uncertainties which will guide future research.

2 Integrated Concept Development

2.1 Overview

It is generally established that the combination of physics and engineering considerations into an integrated solution is a complex problem and usually requires manual treatment and input from dedicated experts in the respective fields. In order to achieve a more automated method, models must be developed which capture the leading characteristics of the components or sub-components and their interactions with other elements within the system. Depending on the element, the level of abstraction for the describing model can vary substantially. Translating this for the case here, the engineering models which describe components within the fusion power plant are treated mostly by analytical or semi-empirical models while the specific plasma transport and confinement is treated with an extremely detailed model including kinetic simulations of the plasma.

In order to bridge the gap between the sophistication and thus time-consumption of these models, individual tools are employed for the engineering and physics design respectively. For the engineering description a systems code is used which is, abstractly speaking, a combination of many small models which describe individual components in a fusion power plant and some simplified physics models. For the detailed plasma physics and confinement a dedicated transport code is used which calculates the neoclassical and turbulent heat-flux for a given design, but requires more computational time and more effort. Here both tools are coupled indirectly by using the results of either as input for the other. Thus, after a few iterations back and forth between the systems studies and the transport simulations, a design consistent both in engineering and physics is obtained.

In the next section, the systems code approach is explained including an overview over the newly developed models for the HELIAS line and following that the transport simulations are briefly introduced. Finally an example is given and the work summarised at the end.

2.2 Systems Codes

Systems codes, also known as design codes, are simplified yet comprehensive models of a complete fusion facility. Such codes bring together physics, engineering and economic aspects allowing development of self-consistent design points. Furthermore, the sensitivity and robustness of such design points can be tested against variations of important parameters. With this approach especially critical development directions for physics scenarios or technology advancements can be identified necessary to guide future research directions. Following this strategy, dedicated experiments in today's devices may be performed as well as state-of-the-art simulations. With the obtained results, systems codes models can be further upgraded to improve the overall modelling. This is a long-term iterative process as conceptually outlined in Fig. 1.

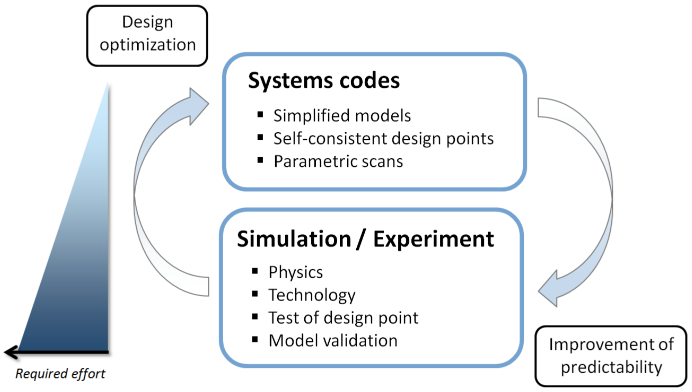

FIG. 1: Concept of systems codes and their interaction with detailed simulations and experiments. The left scale illustrates the required effort (in terms of complexity and time) to carry out the individual tasks.

Systems codes are commonly applied in the tokamak community, especially with respect to a tokamak demonstration fusion power plant, also known as 'DEMO', for which many studies are ongoing [3]. Considering confinement concepts with a 3D topology, similar studies have been done for the heliotron concept [4]. However, so far no systems code existed capable of modelling a helical-axis advanced stellarator (HELIAS). Since the development of a systems code from scratch would haven taken several man-years, the existing tokamak systems code – PROCESS [5] – was reviewed and stellarator-specific models were developed and implemented into this framework. This strategy had the additional advantage, that both the tokamak and stellarator concepts can be treated within a common code framework.

PROCESS is a well-established, partly modular, European tokamak systems code that gained maturity through years of development and application. A solver based on Lagrangian multipliers is employed within PROCESS to allow for design optimisation with respect to the descriptive models and constraints. This is done by minimising (or maximising) a user-defined figure-of-merit consistent with the relevant inputs (iteration variables, constraint equations, and limits). The framework of PROCESS consists of detailed, well-developed plasma physics, engineering and economic models allowing for a broad scope of application.

In a first step, the systems code PROCESS has been assessed to identify changes necessary to accommodate helical-axis advanced stellarators. Based on this assessment, HELIAS-specific models have been developed as documented in [6] designed for a systems code approach consisting of three major models:

- First, a geometry model to describe the plasma shape (flux surfaces) based on Fourier coefficients. In position-space the geometry is described by cylindrical coordinates, which have been decomposed in a Fourier series allowing modelling of any arbitrary 3D toroidal surface. Such a formulation allows one to accurately calculate the important geometrical parameters such as plasma volume, surface area and cross-section which have direct impact on e.g. fusion power or neutron wall load. Moreover, it is possible to scale both the minor and major plasma radius by scaling of the corresponding Fourier coefficients making the model very flexible and suitable for a systems code approach.

- Second, a basic island divertor model for the energy exhaust is derived from geometrical considerations, in addition assuming cross-field transport and radiation at the X-point. The model is of analytic nature and combines physics and engineering relations. From the engineering side, the length of the divertor plate is estimated by considering how a helical field line in the scrape-off layer just passes the divertor plate on the inner side but eventually hits the divertor on the outer side where the radial distance is given by the size of the magnetic island. The broadening of the heat along such a field line is estimated by assuming diffusive cross field transport where the time it takes to reach the divertor is determined by the connection length.
- And third, a coil model which calculates the maximum field at the coils, the total stored magnetic energy, and the dimensions of the winding pack has been developed based on the HELIAS 5-B [7] engineering design. For this purpose scaling relations and analytic inductance and field calculations are employed in combination with a critical current density scaling of the superconducting material used, i.e. scalings for both NbTi and Nb_3Sn have been implemented.

It should be noted, that [6] represents the very first work where HELIAS-specific systems code models have been developed. Since the aim of this approach was not only to simulate individual design points but also to carry out parameter variations over wide ranges, a consequent requirement for the developed models was to retain low calculation times (in comparison to more specific codes which require hundreds of CPU-hours for single runs). A particular difficulty has therefore been the reduction of the 3D complexity of the stellarator to lower dimensions in order to shorten calculation times without sacrificing too much accuracy. Although a PROCESS run for a single stellarator design point takes a few minutes compared to a few seconds for a tokamak, this time frame is entirely sufficient for the envisaged applications.

However, the systems code PROCESS employs empirical confinement time scalings to extrapolate the confinement time, i.e. to describe the radial transport of energy in power plant sized devices. But as already discussed in [8], empirical confinement time scalings are not sufficient to confidently predict the confinement properties of a HELIAS power plant. Therefore, in addition to the systems code approach, a 1D transport code [9] is employed to calculate and estimate the neoclassical and turbulent transport and thus provide a more sophisticated estimation of the confinement in the systems studies as is discussed in the next section.

The models described above have been successfully implemented in the systems code PROCESS and, subsequently, a verification study has been carried out as described in detail in [10]. First, W7-X was modeled within the stellarator-representation of PROCESS and compared to the real machine parameters which showed good agreement of the important parameters within 10% deviation. Secondly, a tokamak DEMO case has been modeled by the 3D stellarator modules where the coil module has been adopted using ITER parameters as basis. Moreover, the island divertor model was modified to take into account the tokamak symmetry and continuous divertor plates. The subsequent modelling of a tokamak DEMO using the stellarator modules showed good agreement to the original PROCESS tokamak models with differences of maximum 10%.

2.3 Transport Simulations

In order to make predictions about the expected confinement in next-step HELIAS devices such as power plant scale device, a 1-D transport code [9] is employed which solves the power balance for the electrons and ions and calculates the neoclassical energy fluxes given DKES [11] data sets. Additional anomalous energy fluxes are considered at the plasma edge based on both experimental data from W7-AS [12] and recent gyrokinetic results from W7-X [13]. A detailed explanation of the transport processes and the transport models is beyond the scope of this work, but can be found in the above given references.

In order to carry out predictive transport simulations for a certain design, a suitable magnetic configuration has to be defined. As dedicated configurations for such a next-step device are still a topic of ongoing research, the existing W7-X 'high-mirror' configuration is selected due to its reactor-relevance. The DKES database has been prepared for a $\beta = 4$ % equilibrium to account for finite beta effects. The dimensionless nature of the DKES approach allows a linear upscaling of the magnetic configuration to the desired size. The configuration can be readily replaced once a fully sophisticated magnetic configuration has been developed.

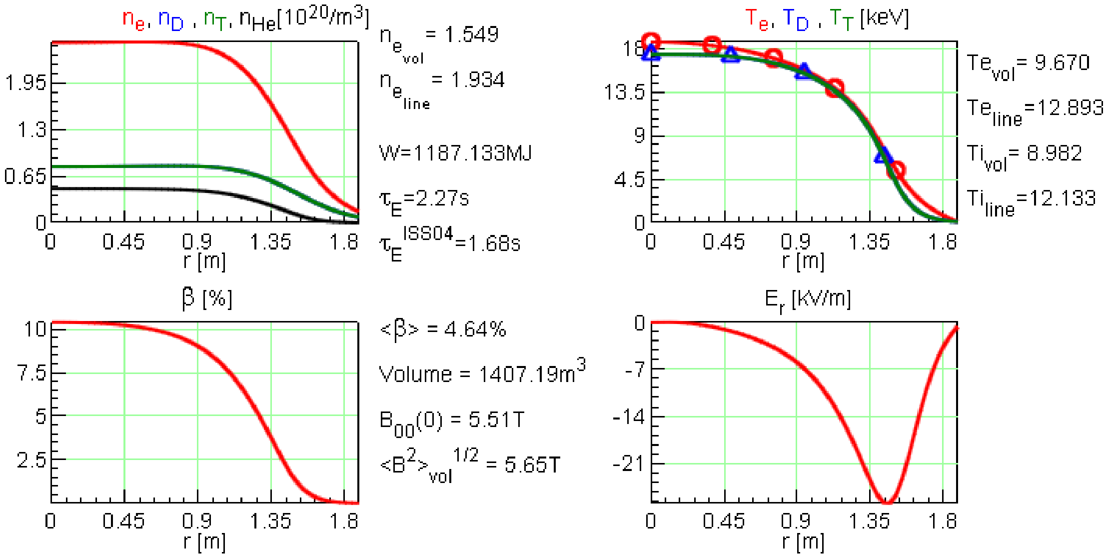

FIG. 2: Profiles for the density, $n_D = n_T$, n_{He}, (top left), temperature (top right), plasma beta (bottom left) and radial electric field (bottom right) for the 1-D predictive transport simulation for a tentative HELIAS reactor case with $R = 20$ m ($A = 10$) and $B_t = 5.5$ T on-axis.

In order to describe the density, a 'standard' profile has been selected and kept constant to avoid a fuelling scenario which requires detailed knowledge of particle sources and sinks. In fact, density control in large stellarators is generally problematic and requires central sources such as pellet injection to avoid hollow density profiles [14]. This is beyond the scope of this work, but will be investigated in future studies.

The resulting density and temperature profiles for a tentative reactor scenario are shown in Fig. 2. The global confinement according to the simulations is in this scenario $\tau_E^{\rm 1D}/\tau_E^{\rm ISS04} = 1.3$ in terms of the empirical ISS04 scaling [15]. As already stated, this result, including the density and temperature profiles and values, are taken as input for the systems code in order to refine the physics properties of the design concept.

The transport simulations could not be directly coupled to the systems codes since the transport simulations can be very time consuming. Therefore, the transport simulations are done for a representative design point in the envisaged engineering parameter regime. Essentially, the simulations provide an energy confinement time τ_E. But in order to use this result for the systems studies it is convenient to rephrase it as an renormalisation factor $f_{\rm ren}$ with respect to the empirical ISS04 confinement time scaling. This 'offset' to the scaling can be directly implemented in the systems studies. Strictly speaking, the obtained renormalisation factor would only be valid for the simulated design point. However, in order to be able to effectively use the systems code, the assumption has been made, that the renormalisation factor is valid in the parameter regime around this reference point. Thus, the empirical confinement time scaling can be used in the systems studies without the need to carry out transport simulations for every design point saving a considerable amount of time and effort. Still, the considered range should not be overextended and checked for consistency. Generally, a few iterations back and forth between the systems studies and the transport simulations are required to arrive at a consistent design.

3 Example

In order to demonstrate the capability of the presented integrated concept development, the methodology has been applied for the helical-axis advanced stellarator line with the aim of defining the accessible design window for a power-plant-sized HELIAS. The major radius and the magnetic field strength on axis were varied over a wide range ($R = 18 - 24$ m, $B = 4.5 - 5.6$ T) with the fixed goal to achieve 1 GW net electric power and an aspect ratio of $A = 12$. The results from this analysis are shown in Fig. 3.

The accessible design window depends strongly on the envisaged beta-limit and the plasma core helium dilution. But even under the most conservative assumptions with a limiting beta at $\beta = 4.5\%$ and 10% helium ash, a feasible design window emerges around $R = 22$ m, $B = 5.5$ T.

4 Summary and Conclusions

In this work an overview has been given over the integrated concept development approach which has been recently devised for next-step HELIAS devices. The focus was thereby set

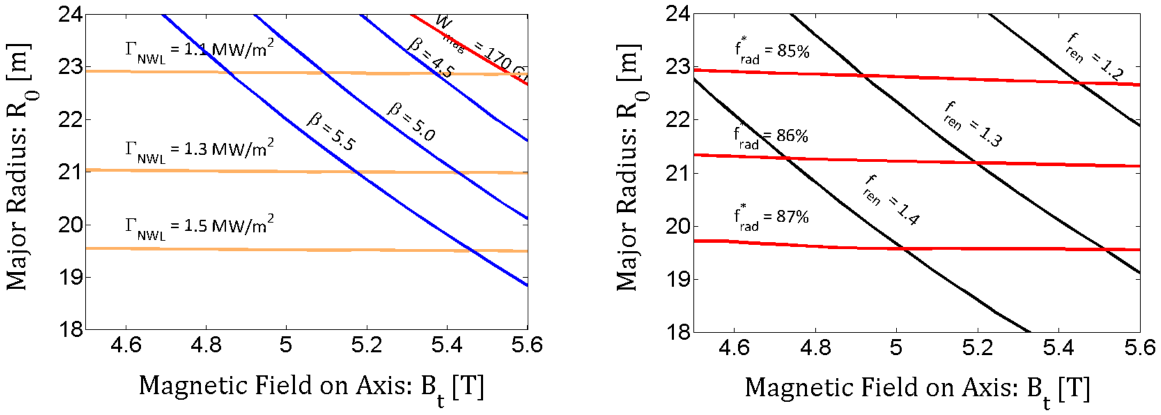

FIG. 3: Design window analysis for a HELIAS power plant device with 10% helium ash concentration constrained to achieve $P_{\mathrm{net,el}} = 1$ GW = const. showing isocontours of the volume-averaged thermal plasma β (blue), the average neutron wall-load (orange), and the stored magnetic energy (red) [left]. Complementary are shown the isocontours of the confinement enhancement factor f_{ren} (black) and the radiation fraction of the power crossing the separatix to keep the peak heat load on the divertor plates at 5 MW/m^2 (red) [right].

on the employed tools, namely systems studies and transport simulations and in particular their interaction. Such a systemic approach allows to design consistent next-step HELIAS devices and further to find optimal solutions by variation over a large parameter space and sensitivity studies; a great advantage over previous point studies.

However, the concept development of next-step devices is an evolving process. New insights regarding plasma confinement, technology and engineering solutions as well as limitations can be continuously used to update the existing models and consequently improve the concept development as a whole. Therefore, the integrated concept development is a valuable methodology in order to help prepare a review point (to be expected in the next decade) which will decide about the future strategy of stellarator research in Europe.

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