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From W7-X to a HELIAS fusion power plant: On engineering considerations for next-step stellarator devices

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1. Introduction

The European consensus for the realisation of commercial fusion energy includes the construction of a demonstration fusion power plant, often simply referred to as 'DEMO' [2]. Although DEMO will be a smaller scale prototype plant, it must prove that a workable solution exists for all reactor relevant physics and technology questions [3].

Following in the line of ITER, the current conceptual design of such a DEMO plant concentrates on the more advanced tokamak concept. However, with the recent start of operation of Wendelstein 7-X, the helical-axis advanced stellarator (HELIAS) line also needs consideration. Assuming that W7-X will demonstrate the success of stellarator optimisation, the future of the HELIAS concept must be discussed including the option for next-step HELIAS devices which are to follow W7-X. In particular the motivation and boundary scenarios for an intermediate-step stellarator which may bridge the gap from W7-X to a stellarator power plant have been discussed recently [4]. The focus was thereby on two boundary cases with different technological sophistication. Option A, a fast-track, cost-efficient device with low magnetic field and without a blanket with the aim to answer all remaining physics questions. And Option C, a more technologically advanced device similar to a demonstration power plant with a full blanket and net electricity power production. Option B would be any compromise between these boundary cases.

However, the latest advancements of the stellarator concept concentrated on physics issues while DEMO relevant technology development focused on tokamak aspects, thus leaving a gap in discussion regarding stellarator-specific engineering and technology considerations. Therefore, this paper attempts to start a more detailed discussion for engineering and technology aspects of next-step HELIAS devices. Issues and advances regarding the magnet system are discussed in Section 2 important for any of the next-step Options. Blanket considerations which are more focused on Option C or a more DEMO-like device are discussed in Section 3. A more general long-term outlook is given in Section 4 where the electron cyclotron resonance heating system (ECRH) is taken as an example before the work is summarised in Section 5.

2. HELIAS magnet system

2.1. Optimisation of equilibrium and modular coils

The design and optimisation of a suitable magnetic configuration is one of the key research areas of advanced stellarators. Although stellarators exhibit a fully 3-D shaped, helical-structured plasma topology, which leads to much higher 'neoclassical' transport than in axisymmetric devices, the intrinsic 3-D topology offers also positive aspects. In particular, the overall 3-D configurations space of possible stellarator designs is very large and in fact much larger than the configuration space spanned by axisymmetric devices which are limited to two dimensions. While initially the optimisation of stellarators was a necessary prerequisite in order to improve the confinement at high temperatures, it is now becoming an advantageous freedom as more and more aspects can be integrated in the optimisation process. Although this freedom is somewhat limited by engineering constraints it is nonetheless a

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powerful tool for resolving plasma related issues 'by design' rather than relying on favourable operation regimes.

Wendelstein 7-X is an example of such an advanced stellarator, including already a considerable number of optimisation criteria, which are listed below [5]:

- Good flux surfaces of the vacuum magnetic field
- Low Shafranov shift, good MHD stability and a stiff equilibrium up to a plasma beta of 4–5% (very low bootstrap current)
- Good energy and particle confinement, i.e., small neoclassical transport losses (drift optimisation)
- A suitable divertor concept for controlled particle and energy exhaust (e.g., island divertor)
- Good confinement of fast particles (i.e., alpha particles)
- Feasibility of the modular coil set (i.e., realistic curvature)

Consequently, one of the high-level goals of W7-X is to assess, demonstrate and verify stellarator optimisation. Already in the first operation phase of W7-X the existence of good flux surfaces could be proven by flux surface measurements [6]. The successful construction and operation of the W7-X modular magnet system also implies the general feasibility of a non-planar coil system. But as W7-X started with a limiter configuration, the demonstration of the island divertor concept and the improved confinement at high performance as well as the investigation of high beta effects can only be approached starting with the next operation phases.

Despite these promising results, it has been recently realised by theoretical studies that the fast ion confinement in W7-X is restricted to a narrow region in the plasma centre [7]. In addition a volume averaged beta of around 3–4% is needed to realise the fast-ion confinement in W7-X by means of the diamagnetic effect.

Therefore, the optimisation of stellarator configurations has recently been more focused on improving the fast particle confinement in next-step HELIAS devices. While HELIAS-type configurations with improved fast particle confinement could be found, so far it remains a challenge to find a suitable accompanying modular coil set. Initial results required therefore an additional set of more complicated 'modulated toroidal coils' [8]. However, for next-step HELIAS devices and reactor-relevant configurations it is essential to keep the coil geometry as simple as possible, not only to save costs but also to reduce the forces acting on the coils. Another strong requirement is to have enough space for large ports in order to ensure a fast replacement of the blanket and first wall.

In order to achieve this, the respective codes belonging to the stellarator optimisation framework ROSE and ONSET [9–11] have recently been upgraded. The major upgrades and achievements (first two points refer to ROSE and third point to ONSET) are the following:

- From now on the coil complexity and form can be directly considered during the optimisation of the magnetic configuration (plasma shape). Consequently, simpler and more suitable coil sets can be found. At this stage ROSE can include the complexity of either modular or saddle coils in the configuration optimisation.
- Also the vacuum and finite-beta equilibrium can be investigated at the same time during the optimisation procedure. This is important as a finite-beta has impact on the transport coefficients as well as through the diamagnetic effect on the fast particle confinement. In particular, now the finite-beta equilibrium can be optimised while at the same time evaluating the vacuum magnetic well.
- The optimisation scope of ONSET has been extended to include a free-boundary calculation of the equilibrium and an evaluation of the resulting VMEC [12] solution along the lines of what is done by ROSE. Although this process is more time consuming, it can help to adjust sensitive parameters more accurately.

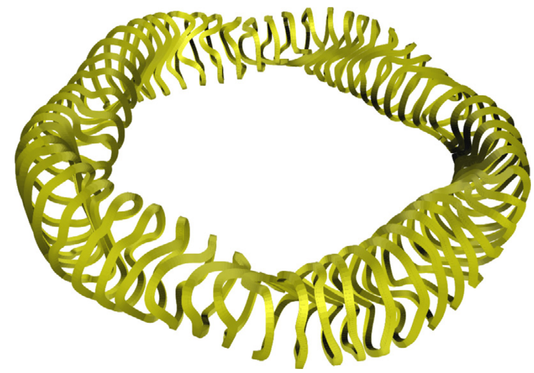

Fig. 1. Tentative modular coil set of a 5-field-period HELIAS-type configuration with improved fast particle confinement and 6 different coil types totaling 60 coils.

A preliminary coil set resulting from the upgraded version of the optimisation framework can be seen in Fig. 1. This tentative 5-field-period design has a higher number of coil-types (6 different non-planar coils compared to 5 in W7-X). The higher number of coils (in total 60 compared to 50 in W7-X) helps to considerably reduce the fast particle losses. It should be noted, however, that this coil set represents a preliminary result and further optimisation and analysis is ongoing.

What has not yet been considered in sufficient detail for the optimisation of magnetic configurations and their coil sets are, from the engineering side: the maintenance access, and from the physics side: the turbulent transport. In fact, turbulent transport was not considered at all during the design of W7-X. However, recent advances in gyrokinetic simulations have found that the magnetic topology has a profound effect on turbulent modes. E.g. in W7-X the trapped-electron-modes are predicted to be partly stabilised [13] and the ion-temperature-gradient modes are anticipated to be localised on a flux-surface [14]. Following this realisation, initial attempts were made to control and reduce turbulent transport by appropriate shaping of 3-D magnetic configurations [15,16]. Although these initial attempts indicate that the turbulent transport can indeed be reduced by tailoring of the magnetic field, a more detailed understanding of turbulent transport in stellarators is necessary. Moreover, it needs to be checked in future studies to what degree turbulent optimisation is compatible with the existing optimisation criteria and coil design. If successful, turbulence reduction may become an important criteria in the integrated configuration and coil optimisation for advanced stellarators in the future.

2.2. Coil technology

Early HELIAS power plant studies concentrated mainly on the NbTi low-temperature-superconductor (LTS) technology which was the state-of-the-art at the time. However, the use of NbTi limited the magnetic field on-axis to about 4.5 T while often still requiring superfluid helium cooling at 1.8 K. However, with the rapid development of superconductor technology and the maturing of Nb_3Sn as superconducting material, presently higher magnetic fields seem feasible. In particular, the properties of Nb_3Sn allow the on-axis field in a HELIAS device to be increased up to 6 T while employing 'normal' helium cooling at 4.2 K. This yields a magnetic field of about 12.5 T at the coils. Although Nb_3Sn is more sensitive to strain than NbTi, Nb_3Sn technology is still compatible with the complex 3-D shape of the modular coils. In fact, the curvature of the coils decreases with increasing coil size making it easier to wind the coils than in W7-X while reducing strain. Apart from Nb_3Sn, also