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# Development of the Wendelstein Line towards a Helias Reactor

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## Main concept of the Wendelstein line and reactor design criteria

The Helias (Helical Advanced Stellarator) reactor is based on the Wendelstein stellarator line and takes into account the design criteria of a power reactor. Wendelstein 7-X, which is now under construction at IPP Greifswald, Germany, is the largest machine in the Wendelstein series of experiments, which combines the achievements of previous physical investigations with modern technical innovations. The optimized properties of this stellarator [1] are defined by the shape of the last closed magnetic surface. The coil system was computed afterwards using the NESCOIL code developed by P. Merkel [2].

The superconducting modular coils are the main technical components of the device and must reconcile the often conflicting physical and engineering demands placed upon them. In order to have an easy-to-handle tool for extrapolation of Wendelstein 7-X towards a power reactor, the code MODUCO (MODUlar COils) has been developed, which allows an interactive modification of the coil design, followed by a computation of magnetic surfaces as well as by a magnetic field evaluation inside the coils. A straightforward scaling of the Wendelstein 7-X experiment leads to the 5-field period reactor configuration HSR5/22 with minimized Pfirsch-Schlüter currents and a subsequently reduced Shafranov shift [3]. In order to reduce the size and the costs of the machine, also 4- and 3-period configurations, HSR4/18 and HSR3/15, were considered [4, 5]. All three options can be modelled with the code MODUCO (Table 1, HSR5M, HSR4M, HSR3M based on extrapolated Wendelstein 7-X coil shapes) and serve as a basis for further optimization studies.

## Modelling of the coil geometry with the code MODUCO

MODUCO represents coils in terms of cubic Bézier curves. By varying their control points the impact of modifications on the structure of the magnetic surfaces can be easily

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investigated. This gives a possibility to represent a large spectrum of coil shapes with a fixed number of parameters, and can be used for stellarators as well as for tokamaks.

The basic principle of coil representation is the following: the core of the coil is a closed curve which is called the central filament. This central filament consists of several segments which are described by cubic Bézier curves with a continuous tangent vector (Fig. 1). A minimum of four such segments is needed to represent a closed coil. Each of the segments is defined by 4 points in space $P_1$, $P_2$, $P_3$, $P_4$ where $P_1$ and $P_4$ are the endpoints of the curve and $P_2$, $P_3$ define the tangent vector at the endpoints (neighbouring segments have identical tangents at the common point). A larger number of segments offers the opportunity to introduce additional flexibility and to increase the quality of the model. A satellite curve having the same structure as the central filament defines the orientation of the coil cross-section. It was found that 4 segments are sufficient to model a large class of modular coils: D-shaped tokamak coils, l=2 stellarator, Heliac, Heliotron-J. More complex coil geometries require an increase of the number of segments. Fig. 2 depicts HSR5M configuration modelled with the approach described above.

## Extrapolation of Wendelstein 7-X towards a Helias reactor

Coils of Wendelstein 7-X can be represented accurately by cubic Bézier curves with five segments, which assures their further scaling and study at reactor dimensions. Due to the optimization, the vacuum and finite-beta magnetic fields in Wendelstein 7-X differ only slightly. That is why an initial modelling of the main parameters of a stellarator reactor can be done by proper shaping of the vacuum configuration.

In addition to coil geometry, the code MODUCO computes magnetic field lines and magnetic surfaces of a given coil system. Besides B, the gradient $\nabla B$ is calculated, and together with the normal vector of magnetic surfaces the geodesic curvature of field lines is given. These values can be used to optimize physical parameters such as parallel current density and radial drift of guiding centres. For this purpose a Biot-Savárt approach is sufficient where the coils are represented by the central filaments.

Calculation of magnetic fields inside the winding packs (Fig. 3), which determines the choice of the superconductor, requires more elaborate methods, taking into account the finite size of the coils. This can be done, for example, using the EFFI approach [6], where the winding pack is decomposed in a set of straight rectangular beams, and the magnetic field of these segments is given in terms of analytic functions.

Regarding the impact of the Bézier approximation on the shape of magnetic surfaces, the main difference was found in the size of the islands at the boundary, while the difference for closed magnetic surfaces is insignificant. Fig. 4 represents comparative simulation results for the rotational transform and Pfirsch-Schlüter currents. The rotational transform on the axis is $\iota(0) = 0.86$ in Wendelstein 7-X and $\iota(0) = 0.88$ in HSR5M, which is based on the Bézier approximation. Such basic optimization features of Helias configurations as the reduction of Pfirsch-Schlüter currents and Shafranov shift are nearly unaltered by the cubic approximation of the central filaments. The magnetic well is around -1.0% for both configurations.

High performance superconductors which are compatible with the field strength requirements of fusion reactor coils have been developed continuously over the years. Advanced $Nb_3Sn$ as well as more strain resistant $Nb_3Al$ have been successfully brought to a level suitable for large-scale applications [7-9] and can be considered as a serious option for a Helias reactor. It is even conceivable that by the time of the design of a demo-reactor high temperature superconductors will be available to be used at temperatures on the order of 20 K and above [10]. Therefore, the induction at the coils of a Helias reactor can be safely increased to 13 T. Previous studies, based on NbTi at 1.8 K, gave a limitation of 10 T on the coils and 5 T on the plasma axis. Both conductor variants are represented in Table 1 by an example of HSR5M. With an advanced superconductor the field in the plasma can be increased, and, hence, the confinement properties can be improved. One also has the additional advantage of operating the magnet at significantly higher temperatures with correspondingly better cooling efficiencies and higher heat capacities of the materials, and/or the option to decrease the coil cross-sections in order to gain more space. For the Helias, a first coil design iteration could be based upon the composition of the ITER toroidal field coil [7]. The maximum field of a Helias reactor will probably not be limited by the superconductor characteristics but by the mechanical structure required to support the enormous electromagnetic forces.

## Conclusions

It has been shown that the representation of various reactor coils can be done with sufficient accuracy using cubic Bézier curves. For Wendelstein 7-X it is enough to use five Bezier segments to reconstruct the modular coil shapes. The new simulation tool, MODUCO, realises this approach and computes important plasma parameters as well as the magnetic field outside and inside the coils, which can be used as input for further structural analyses. The modelling of the 5-period Helias reactor configuration with the MODUCO code confirmed the persistence of the main optimization principles used for Wendelstein 7-X. It was estimated that the magnetic field inside the coil winding pack stays below acceptable limits for the superconductor. The flexibility and easy handling of the MODUCO code makes it a versatile tool for a practical simultaneous optimization of physics and engineering parameters, in particular, for compact Helias rector versions, such as HSR3 or HSR4.

| | W 7-X | HSR5M | | HSR4M | HSR3M |
|---|---|---|---|---|---|
| R [m] | 5.5 | 22 | | 18 | 15 |
| a [m] | 0.5 | 1.8 | | 1.95 | 1.52 |
| $\iota$ on axis | 0.86 | 0.88 | | 0.77 | 0.54 |
| $\iota_{LCMS}$ | 0.96 | 0.96 | | 0.80 | 0.60 |
| <B> on axis [T] | 3.0 | 5.0 | 5.5 | 5.0 | 5.0 |
| $B_{max}$ on coils [T] | 6.6 | 10 | 12 | 10 | 10 |
| superconductor | NbTi | NbTi | $Nb_3Al$ | NbTi | NbTi |

**Table 1** Various Helias configurations, modelled with MODUCO.

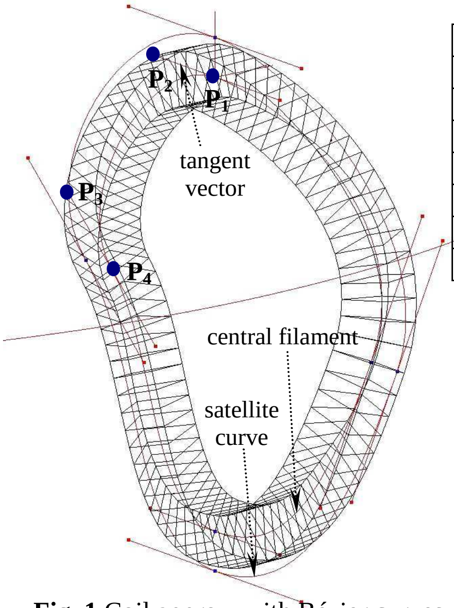

**Fig. 1** Coil approx. with Bézier curves.

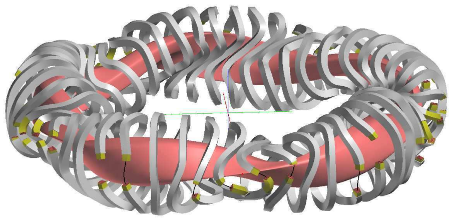

**Fig. 2** HSR5M, modelled with MODUCO.

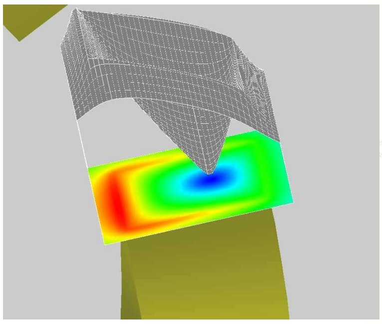

**Fig. 3** Mod B inside the coils (HSR5M).

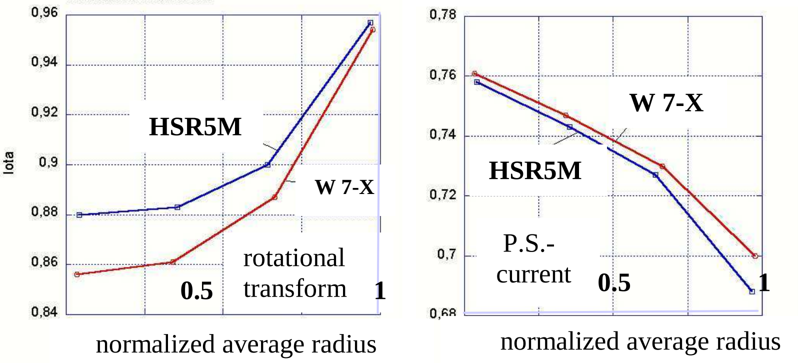

**Fig. 4** HSR5M in comparison with Wendelstein 7-X (W 7-X).

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