# Coil System of a Helias Reactor

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### Abstract

The magnetic fields of Advanced Stellarator configurations can be generated by 3D-shaped modular coils. The shapes of these coils are calculated for a given Helias field configuration. This method allows one to optimize the field according to criteria of optimum plasma performance in a preceding step. The coil system of the Helias reactor considered here, is roughly four times as large as the Wendelstein 7-X device and produces about the same field configuration. The maximum field strength of 10T at the coils is small enough to use NbTi superconductors at 1.8K. The 'cable-in-conduit' conductor is designed for a nominal current of 37.5 kA and has an aluminium alloy jacket. In order to reduce the maximum field on the conductor, the winding pack of each coil is split into two rectangular parts with 9x16 turns each. These two sub-winding packs are in a common enclosing coil housing with a central web for mechanical stiffening. The coils are mutually connected by support elements forming a toroidal vault. Finite-element calculations show that the coils tend to become more circular and planar under the magnetic force load and require local reinforcements of the coil housings.

## 1. INTRODUCTION

In a stellarator all magnetic field components which are necessary to confine the plasma are produced by the external coil system. In the past many systems have been proposed and realized; they were optimized according to various criteria such as simplicity, flexibility and reactor relevance. The combination of helical windings, planar toroidal field (TF) coils and vertical field coils, installed in most of the sellarator devices, is of advantage for experiments since it provides a large amount of flexibility. However, helical windings have only a limited potential regarding field optimization with respect to plasma confinement und stability und pose severe technical difficulties due to the interlinked TF coils. The concept of modular coils as used in the Helias Reactor, see Ref. [1], overcomes these difficulties by needing only one coil system. Furthermore it offers a wide range for field optimization and thereby provides access to the realization of an Advanced Stellarator. The optimization procedure concerning the design of a Helias power reactor which ensure ignition, sufficient space for blanket and shield, a field strength at the conductor small enough to apply NbTi superconductors, and a fusion output of about 3 GW, have resulted in a device roughly four times as large as the Wendelstein 7-X device. Concerning the development of a commercial fusion reactor a burn experiment might be required as an intermediate step to demonstrate the physical and technical viability of the concept. A Helias burn experiment can have a somewhat diminished size, if the condition of self-sustaining tritium breeding is dropped. Table I summerizes the main data of the Helias power reactor HSR and the burn experiment HSB.

TABLE I. MAIN DATA OF HSR AND HSB

| | | HSR | HSB | | | HSR | HSB |
|---|---|---|---|---|---|---|---|
| Av. major radius | [m] | 22.0 | 18.0 | Av. coil radius | [m] | 5.4 | 4.4 |
| Av. plasma radius | [m] | 1.8 | 1.5 | Number of coils | | 50 | 50 |
| Plasma volume | [$m^3$] | 1400 | 770 | Virial stress | [MPa] | 158 | 130 |
| Rotational transf. | | $.84 \div 1$ | $.84 \div 1$ | Stored mag. enery | [GJ] | 100 | 54 |
| Num. of field periods | | 5 | 5 | Average beta | [%] | 4.5 | 4.4 |
| Mag. field on axis | [T] | 4.75 | 4.75 | Tot. mass of core | [t] | 40000 | 26500 |
| Max. field on coil | [T] | 10.0 | 10.0 | Fusion power | [MW] | 3000 | 1600 |

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## 2. THE MAGNETIC FIELD AND COIL OPTIMIZATION

The magnetic field configuration of the Helias Reactor is close to the standard configuration of the Wendelstein 7-X (W 7-X) experiment and is accessible in the broad range of possible configurations of W 7-X. In contrast to W 7-X, there is no superimposed extra planar coil set which allows the experiment the variation of magnetic field parameters e.g. the rotational transform and the magnetic mirror ratio. The reactor configuration has a rotational transform $\iota_o = 0.85$ and the mirror ratio on the magnetic axis is about 9% for which good confinement of the highly energetic $\alpha$-particle is predicted. The shapes of central filaments of the coils, located on a toroidal surface enclosing the last closed flux surface (se Fig. 1), are calculated using the NESCOIL-code [2]. The code solves the problem by satisfying the requirement that the fields produced by the filaments be tangential to a given flux surface. This method of calculating the coil geometry after the magnetic field has been specified offers the chance to optimize the field according to criteria of optimum plasma performance as a first step. The geometry of the last closed flux surface completely determines the properties of the confinement region and is the result of the optimization procedure of the magnetic field. The Advanced Stellarator has been developed along this line. Then, in a second step, the geometry of modular coils can be optimized by the variation of the shape of the enclosing surface on which the current filaments lie. The main goal is to provide sufficient space for blanket and shield, to maximize the minimum distance between this surface and the flux surface under the constraints of minimum filament curvature und maximum filament to filament distance; simultaneously the properties of the magnetic field must be maintained. The direct way from the central filaments to finite size coils is to arrange a rectangular cross-section tangential to the enclosing surface. The total field is generated by 50 superconducting modular coils arranged in a five-period toroidal setup. Each period consists of 10 coils and exhibits the stellarator symmetry such that there are only five different coil types. The results of the optimization are shown in Fig. 2, the total coil set from the top, and Fig. 3, the arrangement of the five different coil types in a half field period.

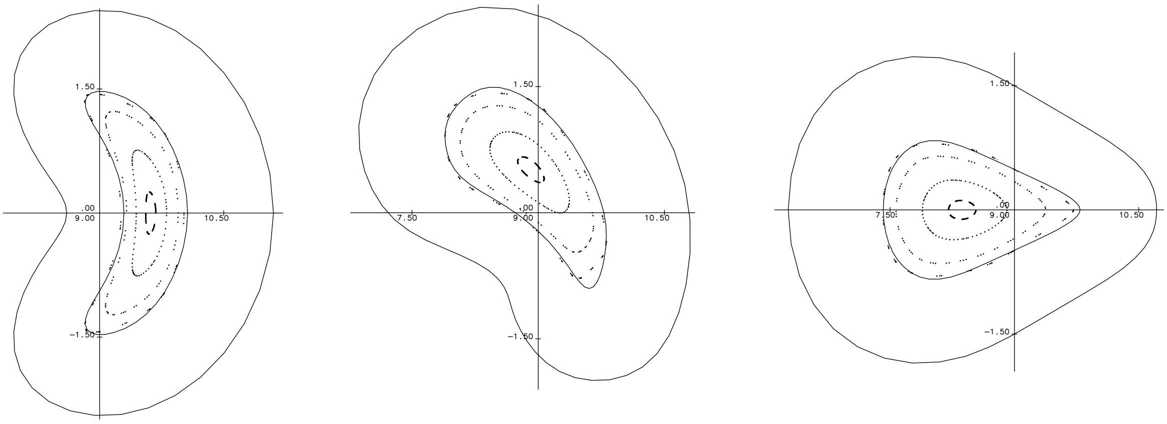

*Fig.1 Cross-section of the given flux surface and the enclosing surface (solid curves) on which the current filaments are calculated at toroidal angle $\varphi$=0, 18 and 36$^o$. The points are a Poincaré plot of the magnetic field calculated from the filaments.*

## 3. THE CONDUCTOR

The first choice is a NbTi superconductor as used in W 7-X. The main advantages of this material are the well-established industrial technology and the good workability. Because of the increased field strength of 10T on the conductor, compared to 6T in W 7-X, the operating temperature must be lowered from 4K to 1.8K, and helium in the superfluid state is used as coolant. Special attention is given to the requirements of non-planar coils by using a cable jacket of soft annealed aluminium alloy. During the winding process the jacket is in a soft stage. Then, after the winding pack is completed, the aluminium jacket is hardend by a heat treatment at moderate temperatures of about 160$^o$ C. Internal forced-flow cooling is preferred because this allows the uniform wetting of the strands close to the superconducting filaments and the fabrication of a monolithic and stiff winding pack. The proposed 'cable-in-conduit'

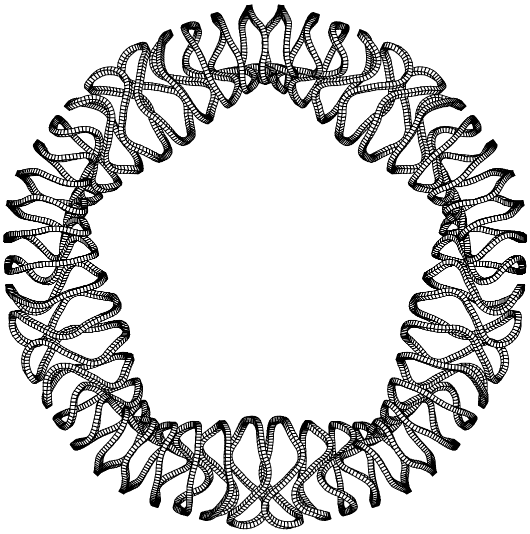

*Fig.2 Top view of the coil set (single winding pack) of HSR*

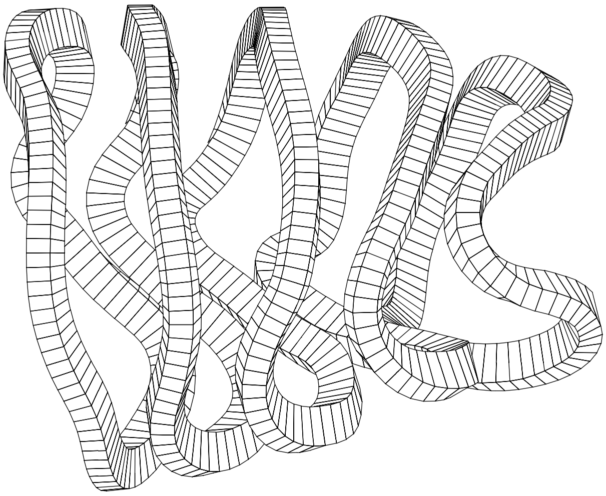

*Fig.3 Coils 1 to 5 (left to right). Shown are the coil housings from the outside of the device.*

TABLE II. DATA OF NbTi CONDUCTOR

| | | |
|---|---|---|
| Overall dimensions | [$mm^2$] | 32x32 |
| Bore diameter | [mm] | 22 |
| Void fraction | [%] | 40 |
| Operational current | [kA] | 37.5 |
| Critical current | [kA] | 71 |
| Overall current density | [$A/mm^2$] | 39 |
| Number of strands | | 192 |
| Diameter of strand | [mm] | 1.20 |
| Twisting structure | | 3x4x4x4 |
| Diameter of filaments | [mm] | 0.05 |
| Num. of fil. per strand | | 192 |
| Fraction Cu/SC | | 2 |

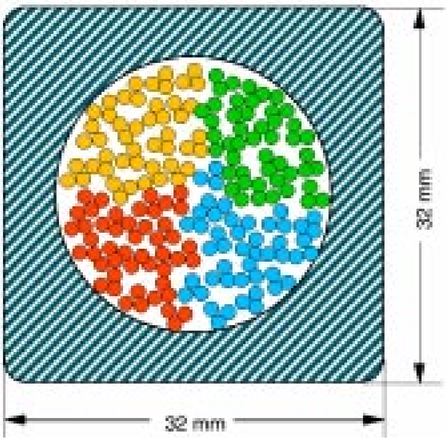

*Fig.4 Cross-section of NbTi conductor*

conductor with a nominal current of 37.5 kA has a quadratic cross-section of 32x32 $mm^2$ and a bore of 22 mm diameter. The superconducting cable consists of 192 strands of pure copper with NbTi filaments of 0.05 mm diameter. The data of the conductor are summerized in Table II; the cross-section of the conductor is shown in Fig. 4.

An increase of the magnetic field offers the chance to use configurations with lower critical $\beta$ values and simpler shape of the modular coils. In this case $Nb_3Sn$ or $Nb_3Al$ superconductor with its technical constraints and the wind and react technique as forseen in ITER must be used. For both materials R&D work is necessary. Because of the lower degradation, resulting from stress and strain, $Nb_3Al$ is the better material, however its stage of technological development is lower.

## 4. COIL CROSS-SECTION AND WINDING PACK

In order to reduce the maximum magnetic field at the coils, various methods were investigated. Current layering and splitting the winding pack were considered. The latter led to a maximum field of 10T at the conductor (field on axis of 4.75T) and allows the use of NbTi superconductors. Furthermore the cooling-length is reduced by a factor of two and the coils are properly aligned to the toroidal geometry. Each coil has two separated rectangular winding packs with 144 turns each and is enclosed in a heavy steel case. This case has a box-type profile with a central web for mechanical stiffening. The main data of winding packs and coils are summerized in Table III; the coil cross-section with split winding pack is shown in Fig. 5.

## 5. COIL SUPPORT

Due to the different local coil curvatures and the slightly helical arrangement of the coils, the force distribution in HSR is inhomogeneous and has radial and lateral components of about the same maximum value on the order of 100 MN/m$^3$. The virial stress characterizes the specific magnetic force load of the coil system and is 158 MPa. The inhomogeneity of the electromagnetic forces on the coils and the high value of the virial stress requires an elaborate support structure. The two winding packs of each coil are surrounded by a stiff stainless steel housing with a thickness of 15 to 32 cm (inner and outer side, respectively). The coils are mutually connected by support elements and form together a toroidal vault. The results of extensive finite-element calculation show a complex stress and strain distribution in the coil and support structure, detailed information is given in Ref. [3]. The coils tend to become more cicular and planar under the magnetic load. This causes bending stresses and related shear stresses in the coils which can be reduced to a tolerable value by local reinforcement of the coil housing at positions with large curvature. An iterative optimization procedure is applied to minimize the amount of structural material and to equalize the stress distribution.

TABLE III. MAIN DATA OF COIL SYSTEM

| | | HSB | HSR |
|---|---|---|---|
| Winding pack | | | |
| Current density | [MA/m$^2$] | 29.6 | 29.6 |
| Total current | [MA·turns] | 8.85 | 10.8 |
| Radial height | [m] | 0.60 | 0.60 |
| Length of cable/coil | [m] | 8980 | 9980 |
| Volume | [m$^3$] | 8.40 | 12.6 |
| Mass of winding pack | [t] | 28.5 | 42.6 |
| Coil casing | | | |
| Radial height | [m] | 1.05 | 1.05 |
| Av. width | [m] | 0.74 | 0.90 |
| Volume | [m$^3$] | 13.3 | 19.9 |
| Mass of casing | [t] | 105 | 157 |
| Mass of support sys. | [t] | 3462 | 6320 |
| Tot.mass of coil sys. | [t] | 10082 | 16210 |

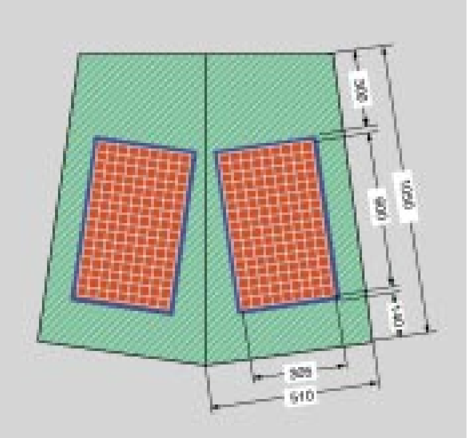

*Fig.5 Split winding pack and coil casing*

## 6. CONCLUSIONS

The coil system of the Helias Reactor consists of 50 modular coils with, because of the symmetry, only five different coil shapes. The coil geometry is calculated after the preceding optimization of the magnetic field configuration. The shape of the coils depends on the field geometry and the distance between the coils and the outermost magnetic surface. The minimum distance is mainly given by the thickness of blanket and shield and is an essential parameter for the size of the device. Because of the low maximum field of 10T at the conductor it is possible to use NbTi superconductor at 1.8K and profit from its well-established industrial technology and good workability. The split winding pack reduces not only the maximum field strength, it allows also a shorter cooling length and a better alignement of the coil housing to the toroidal geometry. The 3D-geometry of the coil system leads to an inhomogeneous distribution of electromagnetic forces and a complex stress and strain distribution occurs. A stiff coil housing with local reinforcements and a system of mutual support elements between the coils keeps the values for stress and strain within technical limits.

References:

[1] C.D. Beidler *et al*, Proc. 16th Int. Conf. on Fusion Energy, Montral (1996),Vol. 3, p. 407

[2] P. Merkel, Nuclear Fusion 27,(1987), p. 867

[3] E. Harmeyer, *et al*, SOFT 1998, to be published