MODULAR COIL SYSTEMS OF ADVANCED STELLARATOR REACTORS

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Only one single super-conducting non-planar coil set is necessary to generate the magnetic field of an advanced stellarator reactor. This concept of modular coils offers a wide range for field optimization with respect to plasma performance. Two HELIAS configurations are considered; one similar to Wendelstein 7-X with 5 field periods and a major radius of 22 m and a more compact configuration with 4 field periods and a major radius of 18m. Both configurations uses 10 coils per period with 5 different coil shapes. The shapes depend on the magnetic field structure and on the distance between plasma and coils. The minimum distance is given by the thickness of blanket and shield and is an essential parameter for the size of the device. The winding packs with trapezoidal cross-sections are split in double pancakes which are wound on steel shells. The trapezoidal cross-section is used in order to reduce the maximum field strength at the conductor on the high-field side. The favoured choice is a NbTi super-conductor because of the established industrial technology and good mechanical properties. Super-fluid helium at 1.8K is used as coolant to ensure safe operation at 10T. More advanced conductors like Nb_3Sn or Nb_3Al offer higher magnetic fields at higher coolant temperatures. Their drawbacks are the lower technological development and brittleness. The magnetic force distribution in the coils is inhomogeneous and has radial and lateral components of about the same value. The coils tend to become more circular and planar under the magnetic load. Stiff coil housings with local reinforcements and a system of inter-coil support elements keep the resulting mechanical stress values within technical limits.

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 stellarator 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. This optimization can be done as a first step and later, in a second step, the shape of the modular coils are calculated with respect to other optimization criteria, e.g. maximum field strength at the conductor and distance between plasma and coils.

The design of a power reactor using a Helias configuration similar to Wendelstein 7-X (5 field periods) which ensures ignition, sufficient space for blanket and shield, a maximum field strength at the conductor small enough to apply NbTi superconductors, and a fusion output of about 3GW, has resulted in a device with a major radius of 22m (HSR5/22). Another device using a more compact Helias configuration with 4 field periods has a major radius of 18m (HSR4/18). In Table I the main parameters of the two devices are summarized. Each field period consists of 10 coils and exhibits stellarator symmetry such that there are only five different coil shapes.

TABLE I: Main parameters of HSR4/18 and HSR5/22.

		HSR4/18	HSR5/22
Major radius	[m]	18	22
Av. minor radius	[m]	2.1	1.8
Plasma volume	[m^3]	1421	1407
Iota (0)		0.83	0.85
Iota (a)		0.96	0.98
Av. magnetic field on axis	[T]	5.0	4.75
Max. field at conductor	[T]	10.3	10
Number of coils		40	50
Magnetic energy	[GJ]	98	100
Mass of coil system	[t]	10400	16200

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 $\iota_0 = 0.85$ and the mirror ratio on the magnetic axis is about 9% for which good confinement of the highly energetic α-particle is predicted. The shapes of central filaments of the coils, located on a toroidal surface enclosing the last closed flux surface (see Figs. 1 and 2), 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. 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 last 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. In order to make the coil shape simpler and tolerate small deviations to the desired field the current filaments are smoothed.

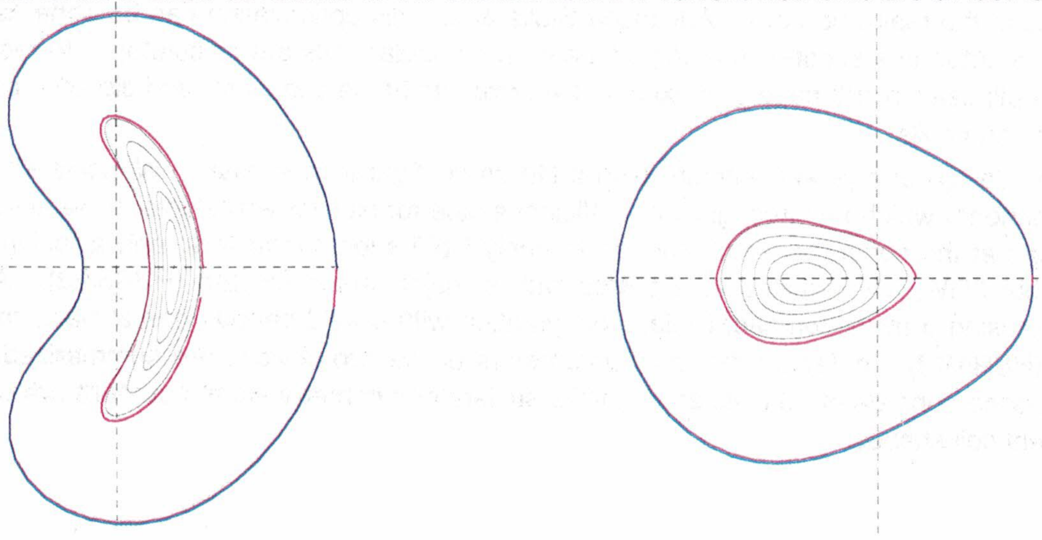

Fig. 1 Cross-section of the given flux surface and the enclosing surface on which the current distribution is calculated at toroidal angles $\varphi = 0$ and 45° of HSR4/18.

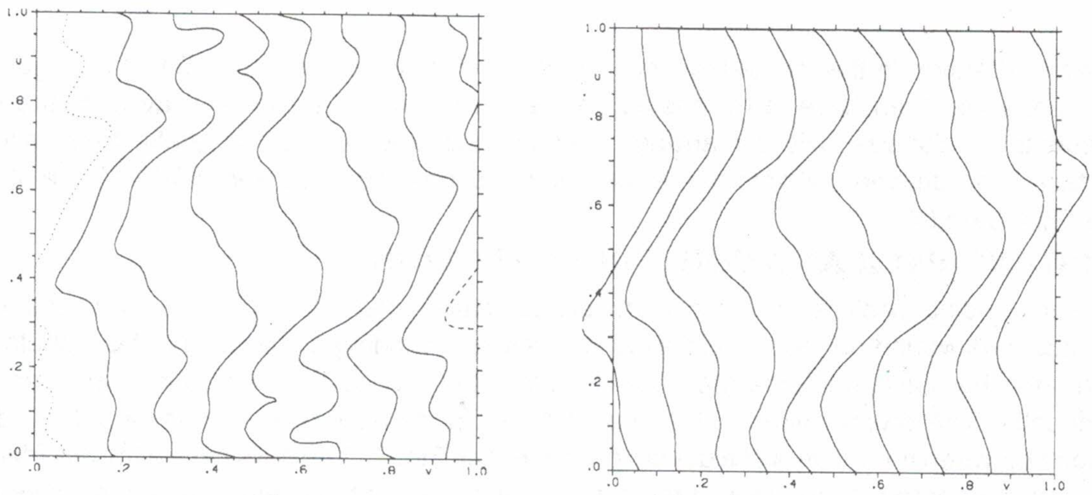

Fig. 2 Current distribution on enclosing surface, left: as calculated by the code, right: after the smoothing procedure.

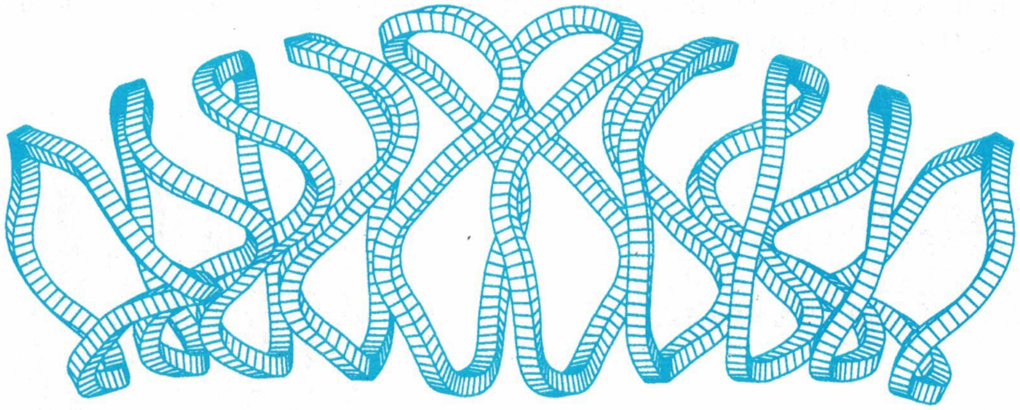

Fig. 3 Coil set of HSR5/22 (winding packs), one field period

TABLE II: Main coil parameters.

Number of turns per coil		288
Length of one turn	[m]	34.5
Cross section of windings	[m^2]	0.4
Cross section of casing	[m^2]	0.24
Volume of winding pack	[m^3]	13.8
Volume of casing	[m^3]	8.5
Weight of conductor	[t]	33
Weight of insulation	[t]	9
Weight of casing	[t]	66

casing without reinforcements

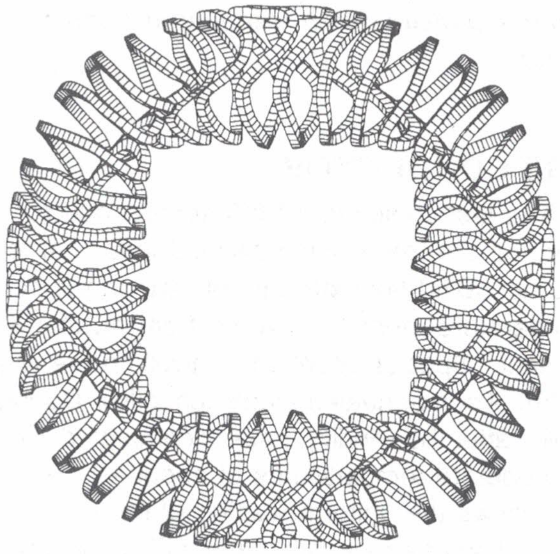

Fig.4 Top view of the coil set (single winding pack) of HSR4/18

Special attention in this procedure must be given to magnetic islands. Small changes in the filament shape can have large effects on the island size. The direct way from the central filaments to finite size coils is to arrange a rectangular cross-section tangential to the enclosing surface. The derived coil sets of the two configurations HSR5/22 and HSR4/18 are shown in the Figs. 3 and 4.

WINDING PACK AND COIL CROSS-SECTION

The winding pack is split into 8 double pancakes consisting of 2x18 turns each. The conductor is wound on steel shells which serves as a winding mould during the manufacturing and later the shells reinforce the winding packs and reduce the mechanical stresses on the conductor. The lowest values for the maximum field and mechanical stresses are derived with a wedge between the 2 layers of a double pancake; see Fig. 5. The coils have a trapezoidal cross-section in order to reduce the average current density at the high-field side and in consequence the maximum field strength at the conductor. The coolant inlet is at the plasma side where the lowest temperature is needed due to the high magnetic field and the heating by fast neutrons coming from the plasma. Coolant outlet and current feeders are located at the radial outside; see Fig. 6. The cooling length is about 620 m.

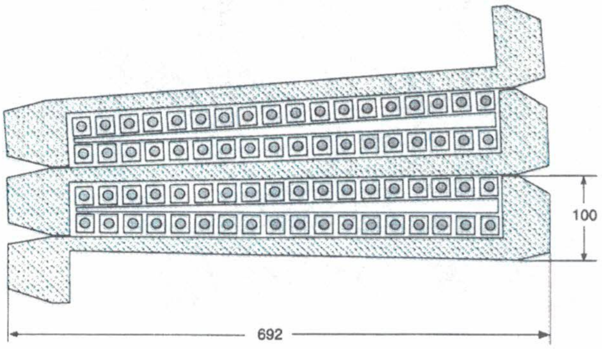

Fig. 5

Double pancake with wedge and winding mould

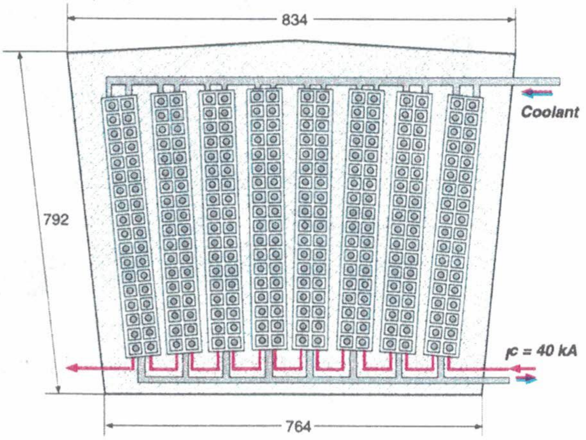

Fig. 6 Coss-section of superconducting coil

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 W7-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° 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' conductor with a nominal current of 40 kA has a square cross-section of 32x32 mm^2 and a bore of 22 mm diameter. The data of the conductor are summerized in Table III; the cross-section of the conductor is shown in Fig. 7.

TABLE III. Data of NbTi conductor

Overall dimensions	[mm^2]	32x32
Bore diameter	[mm]	22
Void fraction	[%]	40
Operational current	[kA]	40
Critical current	[kA]	71
Overall current density	[A/mm^2]	31
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

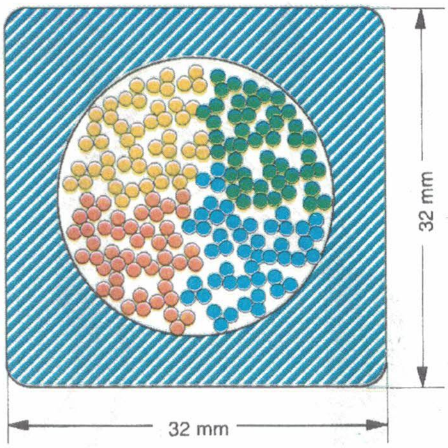

Fig.7 Cross-section of NbTi conductor

An increase of the magnetic field offers the chance to use configurations with lower critical β 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.

MAGNETIC FORCES AND COIL SUPPORT

Due to the different local coil curvatures and the slightly helical arrangement of the coils, the force distribution in the coils is inhomogeneous and has radial and lateral components of about the same maximum value on the order of 100 MN/m^3; see Fig. 8. Due to the radial force components the coils tend to become more circular and planar under the magnetic load. The volume integral of the magnetic force densities results in a net force for each coil with components in radial and vertical direction; see TAB. IV. Basically the net forces are pointing towards the torus center as in a standard solenoid, however on coil 3 the vertical force component of 130 MN is of the order of the radidal component of 163 MN. The maximal centering force of 205 MN acts on coil 1. For an entire field period the total centering force is about 600MN, the net vertical force vanishes, due to the stellarator symmertry. The virial stress characterizes the specific magnetic force load of the coil system and is about 160 MPa. The inhomogeneity of the electromagnetic forces on the coils and the high value of the virial stress requires an adequate support structure. An iterative optimization procedure is applied to minimize the amount of structural material and to equalize the stress distribution. The winding packs of each coil are surrounded by a stiff stainless steel housing. The coils are mutually connected by support elements and form together a toroidal vault. The results of extensive finite-element calculations show a complex stress and strain distribution in the coil and support structure; detailed information is given in Ref. [3]. The tendency of the coils to become more circular and planar under load causes bending stresses and related shear stresses which can be reduced to a tolerable value by local reinforcement of the coil housing at positions with large curvature.

SUMMARY AND CONCLUSION

In a stellarator reactor all fields which confine the plasma can be generated by a single modular coil system. The coil shape is calculated after an optimization of the magnetic field configuration.

Because of the stellarator symmetry only 5 different coil shapes are necessary with 10 coils per period. The shapes depend on the field configuration and on the distance between plasma and coils. The minimum distance is given by the thickness of blanket and shield and is an essential parameter for the size of the device.

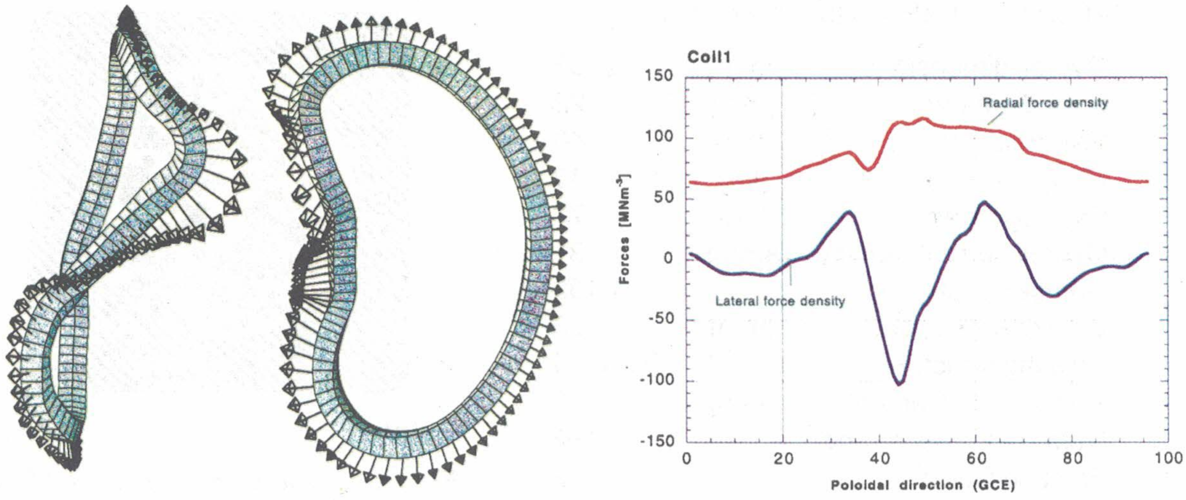

Fig.8 Force distribution on coil 1 of HSR4/18

TABLE IV. Total Forces on each Coil Type (HSR4/18)

Coil	Fr [MN]	Fz [MN]
1	205	-44
2	157	-62
3	163	-130
4	66	-108
5	24	-44

Fig.9 Coil support structure (1/2 field period)

The maximum field strength at the conductor is kept under the limit of NbTi superconductor so that the well-established industrial technology and workability of this material may be used.

The trapezoidal coil cross-section reduces the maximum field at the conductor and steel shells between the pancakes increase the stiffness of the coils and serve as a winding mould.

The 3D-geometry of the coil system leads to a complex distribution of magnetic forces. Stiff coil housings with local reinforcements and a system of intercoil support elements keep the resulting mechanical stress values within technical limits.

References:

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

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СИСТЕМИ МОДУЛЬНИХ КОТУШОК УДОСКОНАЛЕНИХ СТЕЛАРАТОРНИХ РЕАКТОРІВ

Й. Кіссліньґер, С. Д. Байдлер, І. Гармейер, Ф. Гернеґґер, Г. Вобіґ

Для отримання магнітного поля в удосконаленому стелараторному реакторі необхідний тільки один надпровідний неплоский набір котушок. Ця концепція модульних котушок дає можливість оптимізації поля в широкому діапазоні з точки зору характеристик плазми. Розглядаються дві Геліас-конфігурації: одна подібна до стеларатора Вендельштайн 7-Х з п'ятиперіодним полем та великим радіусом тору 22 м та більш компактна конфігурація з чотириперіодним полем та великим радіусом 18 м. Обидві конфігурації використовують десять котушок на період, які мають п'ять різних форм. Форми залежать від структури магнітного поля та від відстані між плазмою та котушкою. Мінімальна відстань визначається товщиною бланкету та екрану і є суттєвим параметром для розміру установки. Блоки обмотки з трапецевидними поперечними перерізами розділяються на дві дискові обмотки, що намотані на сталеві корпуси. Трапецевидний поперечний переріз використовується для зменшення максимальної напруженості поля. Доцільним є вибір надпровідника Nb-Ti, оскільки налагоджено технологію його промислового виробництва, і він має хороші механічні властивості. Надрідкий гелій при температурі 1.8 K використовується як охолоджувач для забезпечення безпечної роботи при $B = 10$ Тл. Використання Nb-Sn або Nb-Al забезпечує більш високі магнітні поля при більш високих температурах охолодження. Їхніми недоліками є нижча технологічна опрацьованість та крихкість. Розподіл магнітної сили в котушках є неоднорідним і має радіальний та поперечний компоненти приблизно однакової величини. Котушки мають тенденцію ставати більш круглими й плоскими під магнітним навантаженням. Жорстке розміщення котушок з локальним кріпленням і системою елементів міжкотушкової підтримки утримує величину результуючого механічного зусилля в технічних межах.