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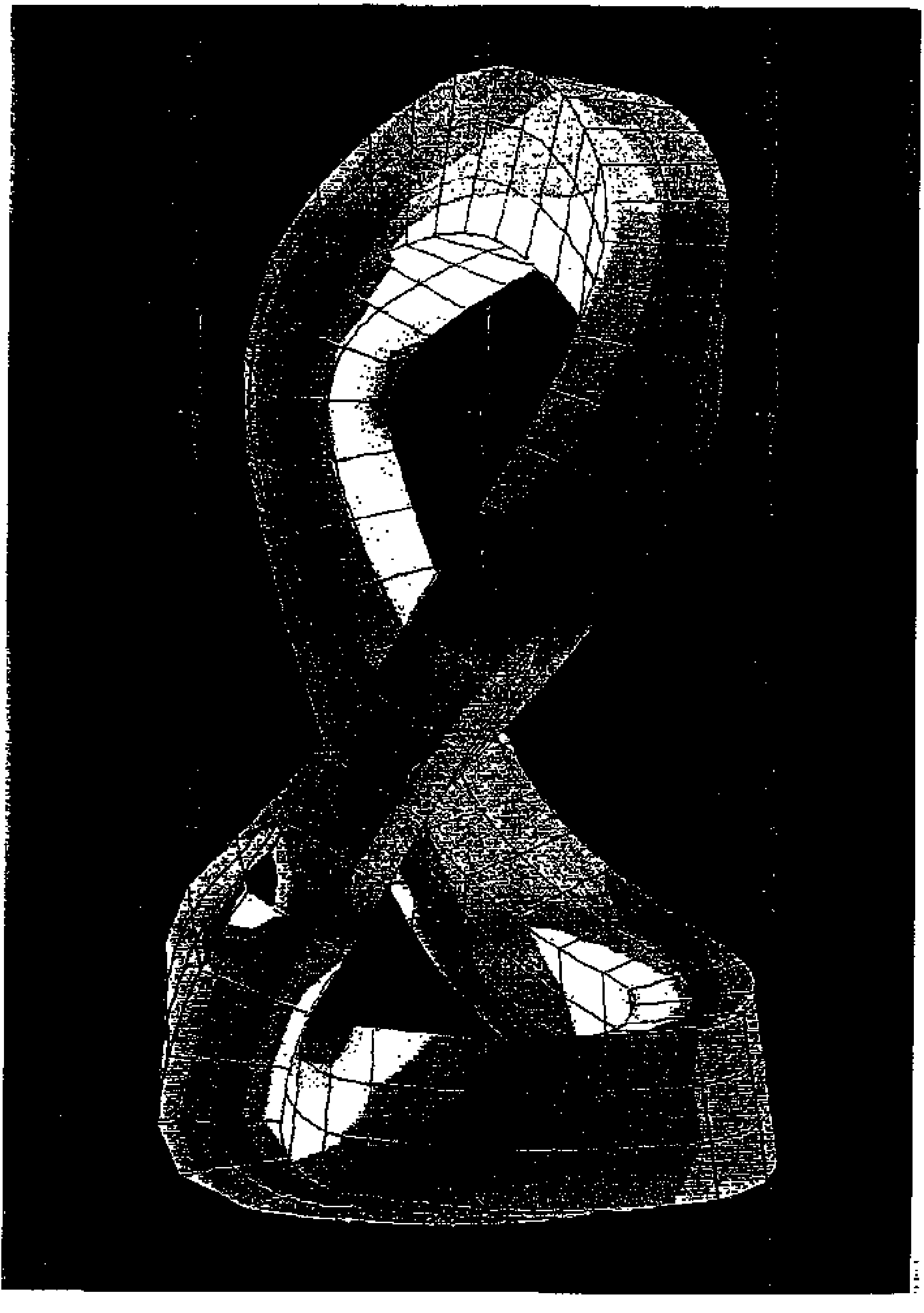

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Modular Coils for the Plasma Experiment Wendelstein WVII-AS

The Max Planck Institute for Plasma Physics in Garching, Federal Republic of Germany, is currently building a large facility for nuclear fusion experiments. In these experiments a new type of coil system will confine the high-temperature plasma by means of magnetic forces, thereby keeping it away from the surrounding walls. The article reports on the design of these coils, which have a very complicated shape, their manufacture, and related problems that had to be overcome.

***K.D. Huber** is in charge of conventional magnets in the Physics Installations and Power Supplies Department of our Power Generation Division.
Mannheim, Federal Republic of Germany*

All over the world today tremendous efforts are being directed towards construction of an economically viable nuclear fusion reactor. Large experimental facilities aimed at turning the fusion process into economic reality are currently in operation, under construction or at the planning stage. The Max Planck Institute for Plasma Physics in Garching, Federal Republic of Germany, is building a large facility for the stellarator experiment WVII-AS which, as a step towards controlled fusion, will be used to test both physical and technical aspects. For this experiment an innovatory coil system is employed.

The purpose of the coil system is to confine the high-temperature plasma within a magnetic field and thus keep it away from the surrounding walls [1-6]. Plasma physics dictates that the magnetic field confining the toroidal plasma must have a twisted shape.

In contrast to earlier coil systems, this twisted magnetic field is achieved by specially formed coils *(Fig. 1)*. The coil shape chosen offers the following advantages:

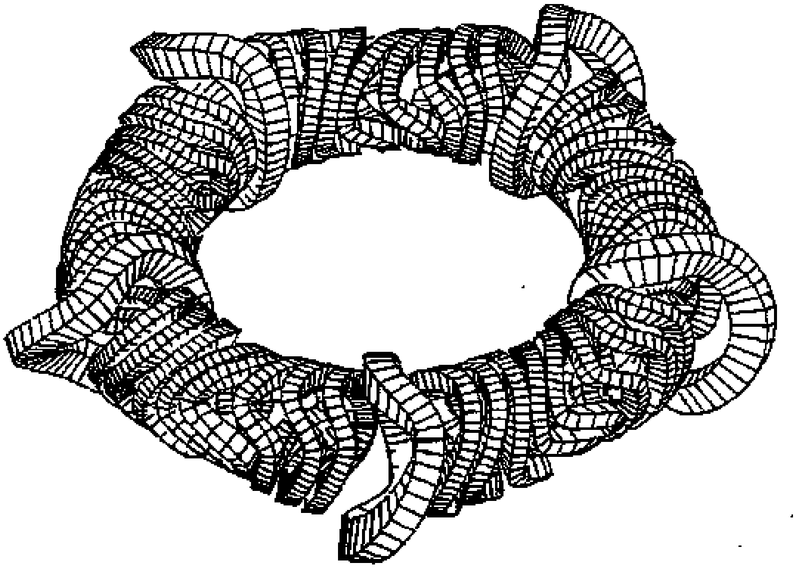
- It reduces the various coil systems to *one* coil set.
- It facilitates a modular construction, which is relevant to the reactor's design.
- It provides good access to the plasma space, thus offering more favourable experimental conditions.
- It avoids the previous helical shape, resulting in improved plasma vessel conditions.

These advantages are gained at the expense of the coil's complicated geometry, which requires a high mechanical strength of both the coil and the materials employed. The forces created by the magnetic field configuration have an additive effect, leading to high combined stressing of the coils.

Coil Concept

Before the contract for the manufacture of a prototype coil and 45 series modular coils was awarded, a feasibili-

Fig. 1 – Coil arrangement for the plasma experiment Wendelstein WVII-AS in the Max Planck Institute for Plasma Physics



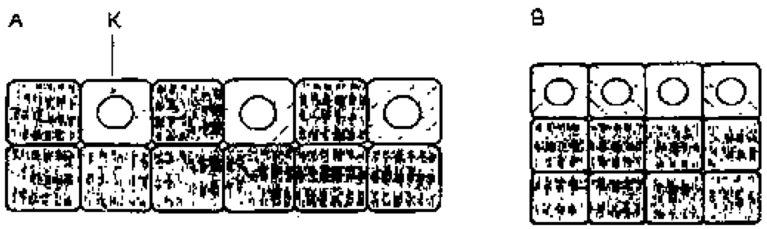


Fig. 2 – Coil cross-sections showing the structure of the bundles with stranded wires and hollow conductors. The stranded wires each consist of 160 strands, 0·8 mm in diameter, with a strength corresponding to F30.

A – Bundle cross-section of small coils
B – Bundle cross-section of large coils
L – Stranded wires
K = Hollow conductors for cooling

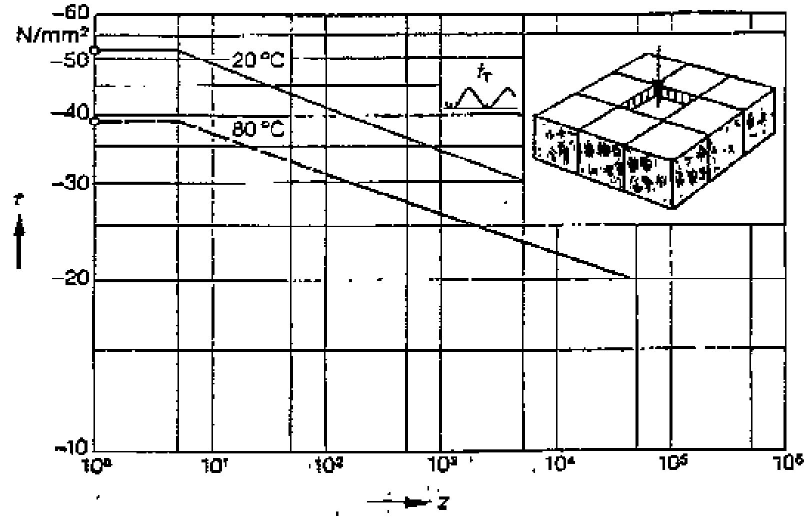


Fig. 3 – Nominal shear strength, determined by dynamic tests carried out on the stranded wire bundle

z – Number of cycles
τ – Shear strength
f_T – Test frequency 0·25 Hz

Technical data of the modular coils used in the Wendelstein project WVII-AS

		Individual coils	
		Coils 1–4	Coil 5
Nominal current	(kA)	37	37
Max. terminal voltage	(kV)	0·1	0·8
Max. conductor to earth voltage	(kV)	4	4
Nominal current density (flattop range)	(A/mm²)	40	40
Number of turns		16	40
Mean turn circumference	(m)	3·6	4·36
Max. overall pulse duration	(s)	13·5	13·5
Min. cycle duration	(s)	210	210
Cold-water temperature	(°C)	27	27
Max. strand temperature (calculated)	(°C)	68·2	68
Flow rate	(m/s)	5	5·5
Operating pressure drop	(bars)	16·5	29
Nominal pressure	(bars)	25	40
Test pressure	(bars)	40	60
Coil weight	(kg)	620	1460
Space factor for stranded wires	(%)	> 81	> 81
Overall space factor*	(%)	> 63·5	> 65·2
Nominal cross-section of bundle	(mm²)	915·5	920·3

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* For maximum coil cross-section and for stranded wires and hollow conductors with nominal dimensions

ty study was carried out. This included an investigation of the manufacturing requirements for coils with such a complex geometry. A practicable concept with a flexible bundle of stranded wires was subsequently developed in which hollow copper conductors, embedded in the bundle, provide cooling.

The hollow conductors, which are far more rigid than the high-strength stranded wires, must be available in the soft state to enable them to be shaped as required. Important features of the chosen concept are:

- Low forces required for shaping; the stranded wires are easily shaped by hand
- Minimum tendency for the shaped turns to return to a planar form
- Minimum 'frozen' mechanical stresses as a result of the winding procedure

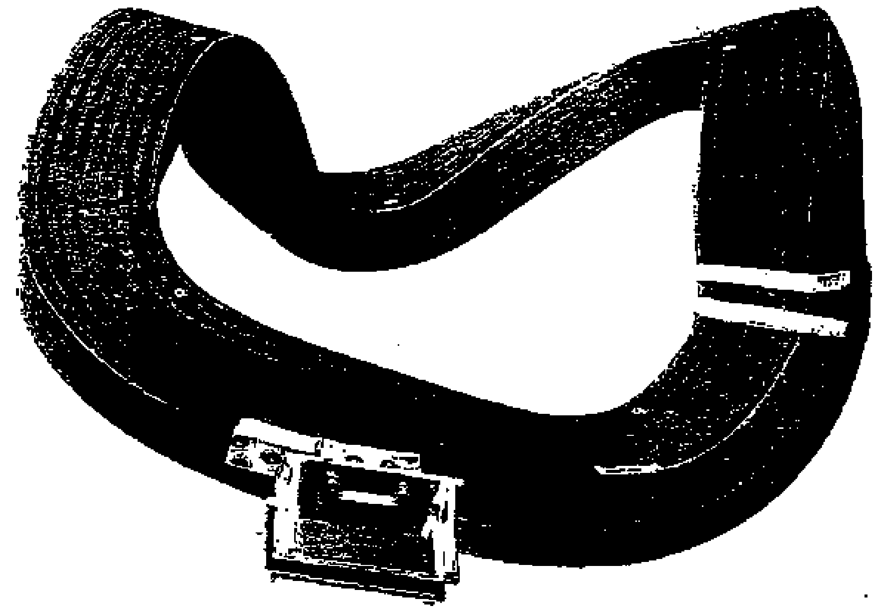


Fig. 4 – Twisted shape of the modular coils used in the Wendelstein WVII-AS plasma experiment

The coil configuration used for the experiment is based on a design with five modules. Within a module there are eight (4 × 2) identically shaped coils and one larger coil in a symmetrical arrangement. Consequently, five different types of coil and their respective forming tools had to be manufactured.

The conductor cross-sections shown in *Fig. 2*(9 stranded wires and 3 hollow conductors for the small coils, and 8 stranded wires and 4 hollow conductors for the large coils) ensure good distribution and uniform cooling. When the coils are operated with a current of 37000 A for the times and intervals shown in the *Table*, the coil temperature rises to an acceptable value not exceeding 86 °C.

The coils' very high mechanical strength is achieved by means of the stranded-wire design and Brown Boveri's ORLITHERM® system of insulation, in which desized glass fabric is combined with a highly flexible epoxy resin. The stranded wires and hollow conductors are bonded by hardening at high temperature in a vacuum pressure process, resulting in a compact and rigid whole.

Comprehensive testing of the materials confirmed the high dynamic shear strength of the coils *(Fig. 3)*.

Coil Design and Manufacture

The coil design is based on a double pancake winding. In this configuration, the stranded wires are continuously wound, starting at the transition from the first to the second pancake. This method requires the material for the second pancake to be fed together with the material of the first pancake in order to avoid any mechanical connection of the stranded wires between the first and second pancake.

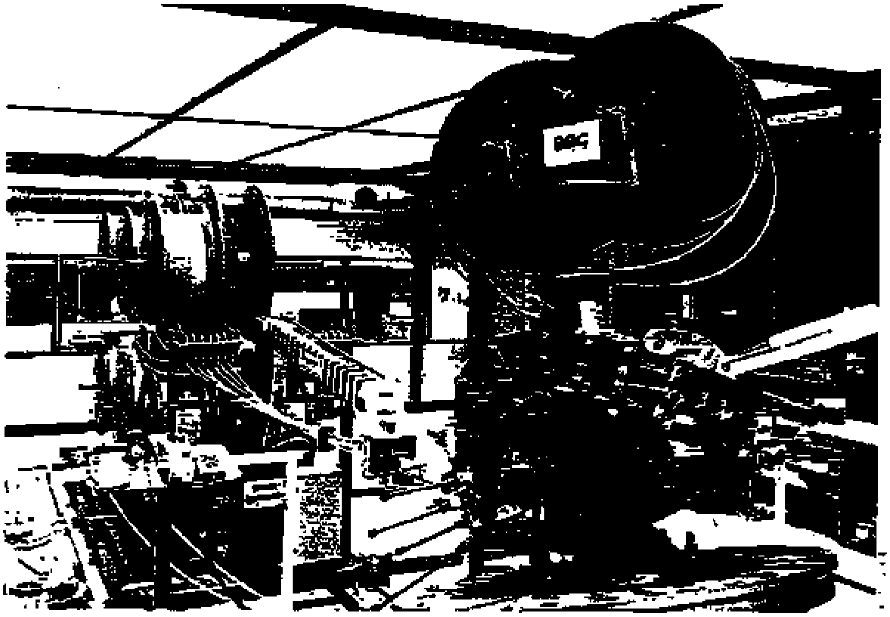
Brown Boveri used combined winding and baking moulds to manufacture the coils *(Fig. 4)*. It is upon the precision of these tools that the exactness of the coils mainly depends. The wire bundles are wound into the moulds in a continuous process, without any major winding tension. The individual stranded wires are wrapped in glass, with the bare hollow conductors lying between them. The turn insulation is inserted during winding of the bundles.

An important feature of the pancake windings' manufacture is their rigidity. This is achieved by each pancake winding being bonded after being wound. The bonding process must not impair later impregnation of the coil, which is why the turn insulation is a pre-impregnated glass fabric.

The outer insulation is applied before the vacuum pressure impregnation with ORLITHERM resin [7]. In this process, the coils lie freely outside of the mould, without any support. After final insulation the coils are vacuum pressure impregnated and baked in the moulds.

Four of the five coil types were measured on a 3D machine to determine deviations from the reference contour. A total of more than 700 measuring points (per coil: 2 coil sides on 2

Fig. 5 – Installation for winding the modular coils. In the foreground is the combined winding and baking mould.



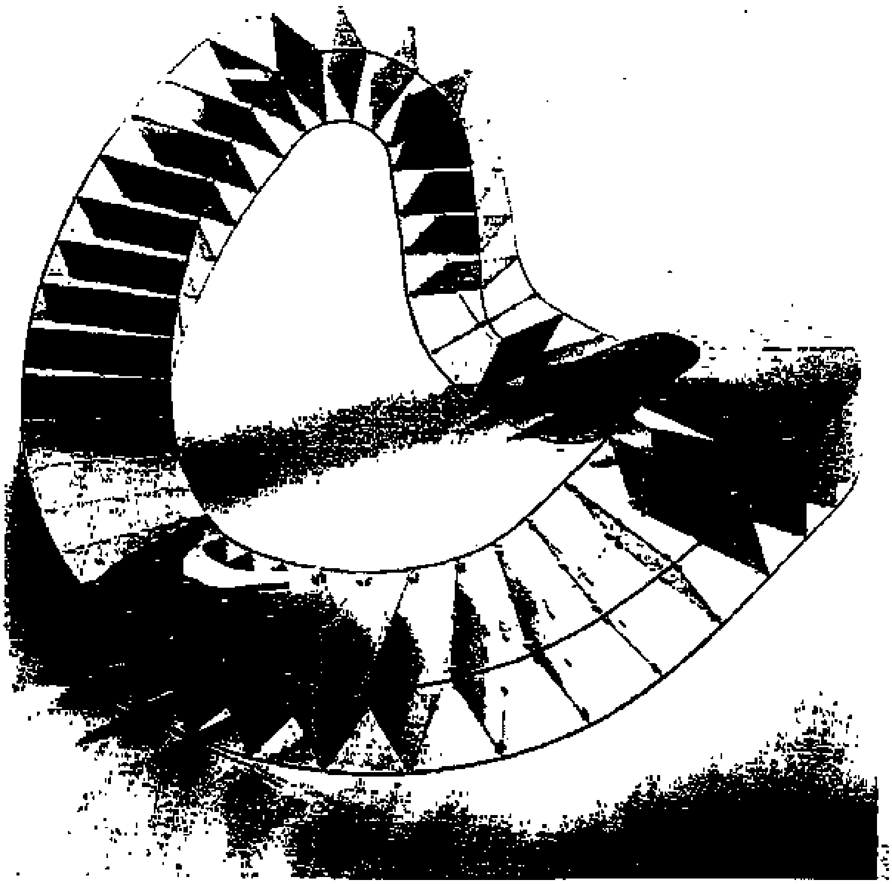


Fig. 6 - Plastic master model used as a basis for tool manufacture

measuring lines) yielded the following tolerances:

Tolerance for coil shape and position	<±3 mm
Relative tolerance for shape and position of coils with respect to one another	<±1 mm
Dimensional tolerance of coil cross-section	±0·5 mm

Coil Forming Tools

The concept chosen for the coil tools is of technical and economical importance for the coil manufacture.

Figure 5 shows a complete winding line with the rotatable and pivotable winder, on which the combined winding and baking mould is mounted, the material store/feeder and the mobile material reels.

The tools are extremely important as they determine the accuracy of both the coils' shape and dimensions/tolerances, as well as the time required for manufacture and the winding sequence. Brown Boveri chose a combined winding and baking mould for each of the coil types. The winding process begins with the mould being dismantled to obtain the shape required for the winding core. Following this, the dismantled parts are refitted and the mould closed on all sides for the prestrengthening, impregnation and curing processes.

So-called 'master' models—plastic models with the maximum coil dimensions—are used to manufacture the tools *(Fig. 6)*. These master models were initially very difficult to make and required extensive testing in order to achieve an acceptable degree of accuracy.

The coils are described mathematically by the four corners of the coil cross-section, forming 48 parts over the periphery. The individual sides of the coil were developed on a single plane using computer-aided design and taking account of the thickness of the plastics material used. The plastic parts were manufactured using an N/C laser cutter.

The outer contours of the coils were obtained by joining the four plastic parts (corresponding to the coil sides) with the aid of appropriate supporting plates. These plates always have the same dimensions (the coil cross-section is constant), and are riveted to the four plastic sides. This method of manufacture ensured a tolerance for the master models (shape and position) of ± 2 mm, referred to the reference contour.

Manufacture of the forming tools began with a wooden model, shaped to the required tool form of the master model. A gap of approximately 10 mm between the master model and the wooden model takes account of distortion and shrinkage of the cast steel mould. The remaining gap between the master model and the steel mould is filled with a synthetic material. Since this synthetic material is poured into the gap, the master model's shape is transferred to the tool with high precision. Good contact between the plastic coating and the steel mould is ensured by indentation, providing a bond capable of withstanding the expected stresses.

The tools are divided into several light and easy to assemble sections. Compression of the coils is also improved by this method.

Materials Testing, Strength Testing and Other Tests

To confirm the coils' ability to withstand high stresses, it was necessary to carry out materials tests in great number before and during manufacture.

Preliminary Tests

The comprehensive test programme undertaken ranged from tests on individual stranded wires through tests on bundles to tests on the assembly with its nominal dimensions (beam with coil cross-section).

The Max Planck Institute carried out mechanical and electrical tests on a prototype coil. These included a test in which the coil was subjected to currents up to 50 kA at 400 V (the nominal stress is 37 kA at 100 V). Only an approximate simulation of the higher shear stress expected later was possible. To achieve full loading, it would have been necessary to know all interactions of the magnetic fields acting in the coil set; this state, however, can only be obtained with the final experimental set-up.

Tests During Manufacture

All coils are put through a comprehensive electrical test programme both during manufacture and when finished. Brown Boveri test the mechanical strength of the coils on the basis of samples taken during manufacture, this strength depending particularly on the quality of the stranded wire. Samples of the individual delivery batches are therefore processed under manufacturing conditions and tested before production begins. Samples of the materials used in each of the coils are also tested parallel to the manufacturing process.

Outlook

Brown Boveri have already delivered most of the coils to the Max Planck Institute, where acceptance tests have been successful.

A follow-up experiment based on the WVII-AS field configuration is being planned at present. The investigations undertaken within the scope of this experiment have already included studies of stellarator reactors, so that it can be assumed that such coil systems will also be employed in the future.

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