

Engineering Problems of the WENDELSTEIN VII-AS Experiment

R. Mathis, J. Sapper, I. Schoenewolf

Max-Planck-Institut für Plasmaphysik, EURATOM-Association, D-8046 Garching, Germany

Abstract

The Advanced Stellarator WENDELSTEIN VII-AS is under construction in the Max-Planck-Institut für Plasmaphysik (IPP) at Garching, Federal Republic of Germany. In contrast to classical Stellarators the confinement field of the new machine is generated by only one set of nonplanar coils. This way the toroidally closed helical windings are avoided and modularity - which is a reactor design criterion - is achieved. The nonplanar coils are supported by a structure outside the coil set. The vacuum vessel is free of magnetically caused helical conductor forces. The construction of the machine requires extended 3D magnetic force and mechanical stress calculations and also a corresponding design. A description of essential machine components is presented. FEM-calculation results and newly developed fabrication methods are reported.

1. Introduction

The Advanced Stellarator WENDELSTEIN VII-AS is a fusion experiment of modular design which is under construction in the Max-Planck-Institut für Plasmaphysik (IPP) at Garching, Federal Republic of Germany. The confinement field of the new machine is generated by only one set of nonplanar coils and not anymore by a combination of a helix- and TF-field as in classical Stellarators. This way the toroidally closed helical windings can be avoided and modularity - which is a reactor design criterion - can be achieved. The vacuum vessel is free of magnetically caused helical conductor forces if the nonplanar coils are supported by a structure which is outside the coil set and which has supporting elements for the lateral coil forces. The new arrangement of machine components for Stellarator field generation avoids some essential design and engineering problems of large Stellarators. On the other side the nonplanar coils together with the geometrically adapted vessel and the structure require extended 3D calculations and also a corresponding design. This paper gives an overview on the design of essential machine components with results from FEM-calculations, as well as for its fabrication methods which had to be newly developed.

2. Machine Components

2.1 Coils

The confinement field of the machine is generated by a set of 45 nonplanar coils (Fig. 1 and 2). The additional system of 10 planar coils is for increasing the experimentally accessible parameter range and allows studies of various confinement conditions. Five of the nonplanar coils are enlarged in size and give space for tangentially arranged neutral injection ports. The set of the nonplanar coils alone generates a toroidal field of $B_0 = 3.0$ T at its nominal line current of 37 kA. Each coil has 16 turns in two pancakes, excepted the enlarged coils which carry 40 turns. The superposition of a toroidal field by the 10 planar coils in co- or counter direction varies the field from 2.5 T up to 3.5 T at a rotational transform t from 0.6 to 0.2 respectively. The standard value of the rotational transform is $t = 0.39$ for the nonplanar coils alone. The material for the coils is a copper/glass/resin compound with internal cooling by hollow copper bars. The nonplanar coils are wound from stranded copper wires (flexible). The mechanical rigidity is achieved by a final epoxy-resin impregnation /1, 2/.

The results of an orthotropic 3D calculation for stress and strain show maximum tensile stress values of 70 Mpa and shear stress values of 20 Mpa at both nominal coil load and temperature (80°C). The calculations were carried out with the program system STELLA (developed in the IPP) which uses the SAP V(2) code for mechanical stress calculation. The model takes into account sliding and elastic bedding of the coil in the support structure (Fig. 3).

The mechanical and electrical qualities of the coil material were investigated with several test methods. At first large series of tensile and shear specimen of the compound material had been tested statically and dynamically. S-N curves from sufficient specimen numbers were gained (Fig. 4). At second test beams with 1:1 cross-section and final conductor arrangement were subjected to cycle tests with nominal tensile and shear load. At third a prototype coil was built and tested electrically, thermally and mechanically. The coil performance will be limited by shear stress in the insulation layers. A lifetime of 50×10^3 cycles was the design criterion /3/.

2.2 Vacuum Vessel

The modularly designed vacuum vessel of the machine is rather accurately adapted to the inside surface of the coil system to achieve maximum space for the plasma column. It is fabricated from 12 mm stainless sheet steel (X2CrNi18 10) and carries 26 port holes in each module. A 1:1 scale test piece was manufactured for proof of principle (Fig. 5). A 3D FE calculation with ANSYS was carried out. Under vacuum forces the calculated tension locally reaches 200 Mpa in the wall at a displacement of 0.8 mm along the small axis of the elliptical vessel cross-section. The same value was found at the test piece.

The vessel is bakable up to 150° C by a hydraulic heating system. The same system will be used for the vessel cooling at normal pulse operation. The thermal movement of the torus is 6 mm in radial direction. Special bearings guarantee the centric position of the torus under cold and hot conditions.

2.3 Structure

The central structure of the machine is a cylinder with top and bottom supporting disks. An additional structure shell around the modular coil system transmits the complex coil forces to the central support structure. The shell is fabricated from 20 mm stainless sheet steel and is also of modular design. A 3D-FEM calculation with the NASTRAN code was carried out. It took into account the interaction between the coils and the shell, and the different material coefficients of coils, bedding, and the shell itself. Figure 6 shows the calculated stress distribution on the shell surface for one half module. Maximum local values are near 240 Mpa (van Mises stress).

The allowed manufacturing tolerance for the contour of the sheet steel construction is ± 3 mm and was reached in practice. Machined surfaces are of the usual high precision /4/.

3. Manufacturing

All newly developed components for WENDELSTEIN VII-AS are under construction in industry. Prototypes have been delivered to IPP and were subjected to various test procedures. The predicted performance could be reached.

3.1 Coils

For the nonplanar coils, a manufacturing method has been established which consists of the following steps:

- Splittable winding and baking moulds obtained from high precision master models (Fig. 7).
- Stranded copper conductors wound into the mould.
- Dry glass/resin insulation during manufacturing with final vacuum pressure impregnation.

Figure 8 shows a prototype coil after the resin impregnation.

3.2 Vessel

The manufacturing method for the vacuum vessel is based on plane evolutions of wall segments which are bent in a press and welded together from the inside of the vessel. With the experience derived from the test piece, a contour accuracy of the elliptical cross-sections of less than ± 5 mm is achieved which is well within the guaranteed tolerances of ± 7 mm.

4. Assembly and Total Arrangement

The assembly of the machine modules and later on of the preassembled modules on the central supporting structure will start in 1985 at the IPP. From the existing W VII-A device the following essential parts will be re-used: the experimental hall, the basement, the central supporting structure with smaller alterations and the energy supply and distribution system, as well as the poloidal field systems. It is intended to keep the interruption of the experimental operation as short as possible. Therefore, the modules for W VII-AS will be preassembled on a separate assembly place. The dismantling of W VII-A will only start after successful preassembling, so that a minimum of time for the assembly procedure can be reached.

References:

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- /4/ Brossmann, U., Kerl, F., Melchior, W., Mukherjee, S., Sapper, J., Sombach, B., "Modular Mechanical Design of the Advanced Stellarator WENDELSTEIN VII-AS", 12th Symp. on Fusion Technology, Jülich, FRG, Pergamon Press, Oxford (1982), Vol. 2, 915.

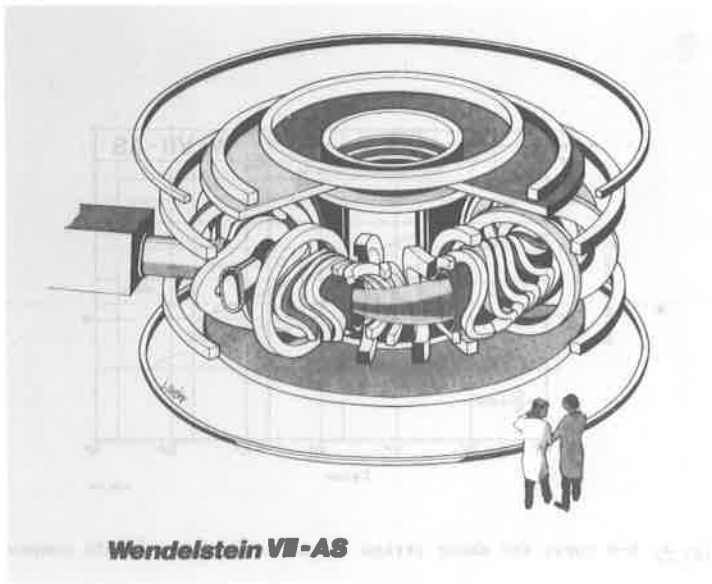


Fig. 1: Total assembly of W VII-AS.

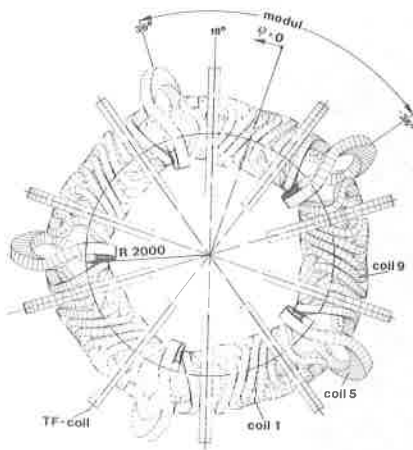


Fig. 2: Coil set for the confinement field.

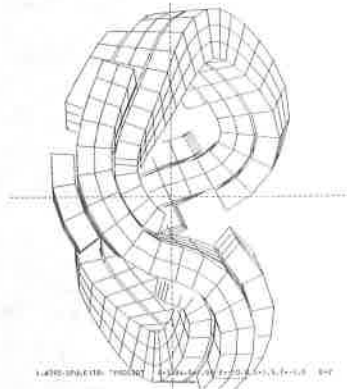


Fig. 3: Finite element model of one nonplanar coil with bedding and structure parts.

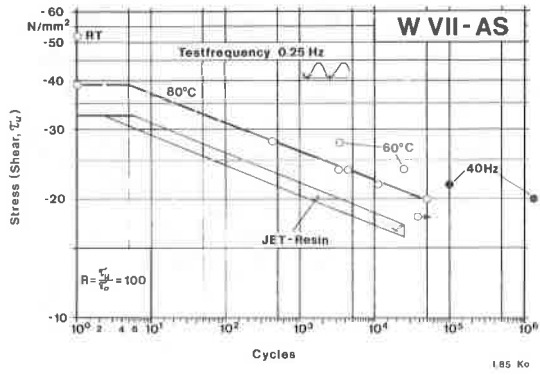


Fig. 4: S-N curve for shear stress in the copper/glass/resin compound.

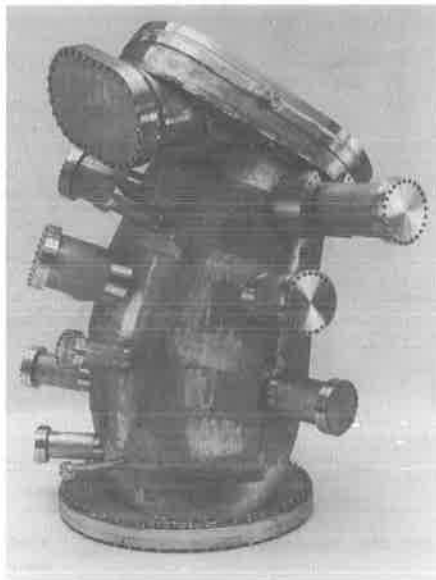


Fig. 5: Vacuum vessel test piece.

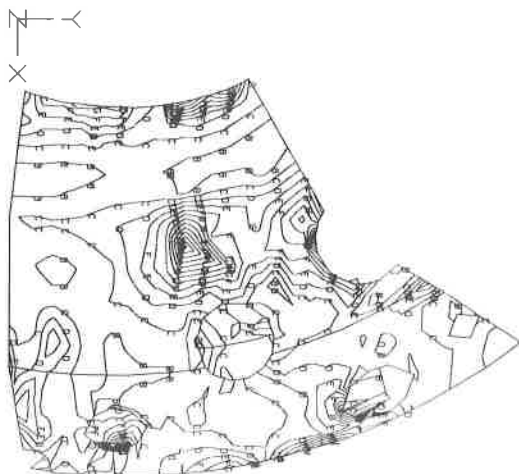


Fig. 6: Stress distribution on the structure shell surface, lines of constant von Mises stress.



Fig. 7: Master model for one of the nonplanar coils.

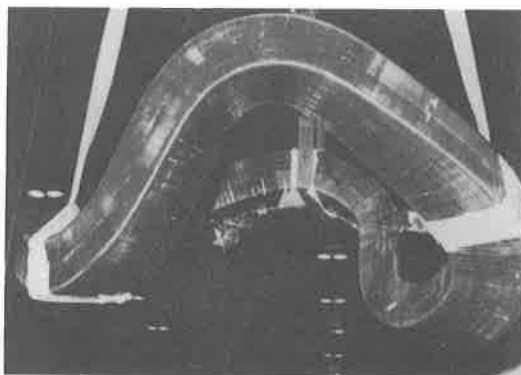


Fig. 8: Prototype coil, after resin impregnation.