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Manufacturing and assembly of the plasma- and outer vessel of the cryostat for Wendelstein 7-X

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ABSTRACT

Wendelstein 7-X is an advanced helical stellarator, which is presently under construction at the Greifswald branch of IPP. A set of 70 superconducting coils arranged in five modules provides a twisted shaped magnetic cage for the plasma and allows steady state operation. Operation of the magnet system at cryogenic temperatures requires a cryostat which provides thermal protection and gives access to the plasma. The main components of the cryostat are the plasma vessel, the outer vessel, the ports, and the thermal insulation. The German company, MAN Diesel & Turbo SE Deggendorf (former MAN DWE GmbH Deggendorf), is responsible for the manufacture and assembly of the plasma vessel, the outer vessel and the thermal insulation. This paper describes the manufacturing and assembly technology of the plasma and outer vessel of the cryostat for Wendelstein 7-X.

1. Introduction

Wendelstein 7-X (W7-X) is an advanced helical stellarator which is presently under construction at the Greifswald branch of IPP. A set of 70 superconducting coils arranged in five modules provides a twisted shaped magnetic cage for the plasma and allows steady state operation. The operation of the magnet system at cryogenic temperatures requires a cryostat which provides thermal protection and gives access to the plasma. The main components of the W 7-X cryostat are the plasma vessel, the outer vessel, the ports and the thermal insulation.

The German company, MAN Diesel & Turbo SE Deggendorf (former MAN DWE GmbH Deggendorf), is responsible for the manufacturing of the plasma vessel, the outer vessel and the thermal insulation.

2. Structure of the W7-X cryostat

The cryostat of W7-X has the shape of a torus and consists of an inner vessel, the plasma vessel, and an outer vessel as shown in Fig. 1. The entire superconducting coil system is contained within the space between the plasma and the outer vessel. This coil system generates a magnetic field in which the plasma is confined.

The thermal insulation of the cryogenic components is affected by high vacuum (HV) together with superinsulation and an actively cooled heat radiation shield. For this reasons the space between plasma and outer vessel is evacuated to a high vacuum with a pressure of <10^{-6} mbar. The space between plasma and outer vessel is called the cryospace. The plasma vessel is evacuated to an ultra-high vacuum (UHV) with a pressure of <10^{-8} mbar. This way the plasma vessel separates the plasma vacuum from the insulation vacuum. The outer vessel separates the insulation vacuum from the surrounding atmosphere. All surfaces facing the cryospace at ambient temperature are equipped with superinsulation and a heat radiation shield at about 80 K.

The ports grant the access to the interior of the plasma vessel through the insulation vacuum.

3. Plasma vessel

3.1. Manufacturing of the plasma vessel [1]

The order for the manufacture of the plasma vessel was placed with MAN DWE GmbH in December 2000. In compliance with a quality management plan, a test and inspection plan for general manufacturing and test instructions was developed.

The manufacturing and sequential test plans describe each of the manufacturing steps, tests and inspections for the manufacture of each half-module sector including all the built-in parts and external mounted parts.

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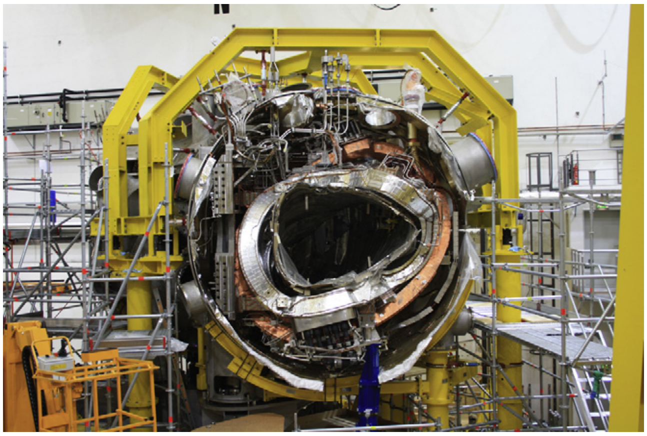

Fig. 1. W7-X cryostat cross section.

Specific steps of production and tests during manufacture were additionally defined in descriptions according to manufacture and work instructions.

For reasons of compatibility and a definite transfer of data, both MAN DWE and the IPP-branch used the CAD-system CADDS5.

MAN DWE carried out extensive studies and tests in order to ensure the manufacture of the complicated shaped geometry of the plasma vessel within the tight tolerance zones.

A model to a scale of 1:5 for a quick visualization of processes was made.

To manufacture the shape of the vessel, MAN DWE decided to use edge-bent rings which are assembled as a torus. One study determined the optimal width of the rings to use the available space between the inner and outer enveloping area as good as possible for the design of the 17 mm thick steel shell. In doing so, the scope of welding had to be minimized particularly with regard to shrinkage in order to achieve the CAD-edge model tolerance requirements. The results were rings with a toroidal division of 1.8° resulting in 200 rings for the complete torus. For manufacturing reasons, each ring is assembled of 4 poloidal segments.

Edge-bending templates were made in order to verify the outline-accuracy of the individual segments in a simple and effective way during bending. During the assembly of the segments as well as during the welding of the poloidal seams, the accuracy of the entire outline of a ring was verified by circumferential templates which were specially made for this purpose.

Correct alignment, positioning and tacking of the individual rings were achieved by measuring dividers and a special table. All segments of the plasma vessel and the single components of the edge-bending and circumferential templates were marked with an identification number in a single operation during the water jet cutting.

After determining the manufacturing process, three sample rings of a half module sector were fabricated. Two more rings, which fulfilled the specified tolerances, were built after the modification of the process. These results made it possible to manufacture segments which lay in the tolerance zone of 45 mm. For the segments with particularly tight tolerances, die-forged parts had to be manufactured by hot-forming. 150 segments out of the required 820 for the complete torus were manufactured as forged parts.

The sample rings were used to investigate the welding shrinkage of Y and X-seams. Both seam types were welded by means of the TIG-cold rod technique. This special technique facilitated the simultaneous double-sided welding of the X-seam. An average welding shrinkage of 1.9 mm for the Y-seam and 2.0 mm for the X-seam could be realised. The decision was made in favour of the X-seam since it does not require any expensive smoothing.

With regard to their dimensions and complex form, the surveying of the test parts was carried out with a laser tracker.

The preliminary tests represented the basis for the manufacturing process which could be initialized with the cutting of the sector rings and the preparation of the welding edges through water jet cutting. Then, the sectors were edge-bent or hot formed and the welding seam preparation was attached. The assembly of each 4 segments in a ring and the welding of the straight seam were carried out afterwards. The 1.8°-sector rings were then milled and the welding edges for the poloidal circumferential joints were prepared. For the primary body of the 9° half module sector, 5 sector rings were assembled and welded with circumferential joints. For the primary shell of the 27° half module sector three 9°-sectors were assembled and poloidally welded.

An integral helium-leak-test of the half module sector was carried out to proof the specified leak tightness of the welding seams. To do so, the ends of the sectors were closed with sheet covers. With this method, the integral leak rate of 10^{-7} mbar l/s could be verified. The cutting of the holes for the ports was carried out with a 3D-water jet cutting plant. The 3DCAD-data could be directly taken for the programming. The test-sector of the three 1.8° rings could be utilized to test the accuracy for the port hole cutting. The shape and position of the holes was then surveyed with a laser tracker and confirmed the compliance of the high demands for dimension accuracy.

For the neighbouring 9° half module sectors, which were still welded together, cutting of the port holes of the non-planar adjusting ring for the module connection as well as the tailoring of the sectors was performed by the water jet cutting technique.

The pre-fabrication of the bearings for the three supporting legs was carried out in parallel to the manufacture of the plasma vessel.

Pipe lengths of 9 m were used for the heating and cooling pipes in order to keep the number of orbital weldings as small as possible. Each pipe was integrally leak tested before it was mounted on the outside of the plasma vessel. One pipe showed a clearly defined leak and had to be removed. The routing of the heating and cooling pipes was marked on the surface of the vessel in compliance with the position of the legs and saddle coils which will have to be installed later. The routing also had to consider the restricted geometrical tolerances. Next, the mounting and the welding of the heating and cooling pipes were carried out. The necessary heat transfer is guaranteed by fillet welds on both sides.

Presently, the brackets for the components inside the plasma vessel are being installed and welded by a positioning robot.

After the completion of these works, the heating and cooling pipes will have to undergo an integral leak test in a vacuum chamber while applying an interior pressure of 90 bar.

Final factory inspection will comprise a check of the dimensions, the cleanliness and a control of the completeness of the documentation.

The manufacture of the first two half-module sectors was finished in December 2003. The manufacture of all 20 sectors of the plasma vessel has been completed in December 2005.

3.2. Assembly of the plasma vessel

In April 2004 the assembly of the plasma vessel was started on the site in Greifswald with the welding of the first welding seam between the half-module sectors of half-module ABB50 (Fig. 2).

The bracket and the pocket of half-module ABB50 were welded in July 2005.

In November 2006 the welding seam between the half-module sectors of half-module ABB51 was welded and in January/February 2007 the brackets and the pocket of half-module ABB51 were welded.