Experiences from the Assembly of the Magnet System for Wendelstein 7-X

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***Abstract*—Wendelstein 7-X represents the continuation of fusion experiments of the stellarator type at the Max-Planck-Institute for Plasma Physics. The size of device (725 t, height of 5 m, diameter 16 m) and the superconductive magnet system distinguish W7-X from earlier stellarators at the Max-Planck Institute. The paper describes the technologies and methods used for the assembly of the magnet system and it compiles the experiences gained. The assembly of the W7-X facility will be accomplished in 2014.**

***Index Terms*—assembly, experiences, superconductive magnet system, Wendelstein 7-X**

I. INTRODUCTION

The superconducting magnet system (MS) is the central component of the Wendelstein 7-X (W7-X) basic machine. It is enclosed by a so-called cryostat, an evacuated system that consists of the outer vessel, the plasma vessel (PV) and 254 ports. The MS consists of five identical modules (Fig. 1); it weighs 425 tons and it is cooled down with liquid helium to about 4 K. The MS consists of 70 superconducting non-planar (NPS) and planar (PLS) coils, a bus-bar system, a helium distribution system and 14 current leads [1], [2]. The coils are bolted to a complex central support structure (CSS). They are sectioned in seven groups; each group has a separate 18 kA power supply. The magnetic field is to be generated by the MS in a torus-volume (diameter ratio of about 10 m/2 m) with a relative overall accuracy of about 1E-4. This requirement has caused expensive developments for the positioning, contour taking, customizing and precision-welding of the associated components. The electrical and hydraulic connections of the components of the MS are challenging, since many handlings had and still have to be done at extremely poor access to many critical areas. The high density of components in the space for installation and the risk of clashes between neighboring components (particularly during the later operation) cause comprehensive configuration-control measures and subsequent correction measures. All five individual magnet modules for W7-X have already been assembled, four of them are put in their final position, and two of them are already connected together.

II. ASSEMBLY SEQUENCE

Each module of W7-X is split into two flip-symmetric semi-modules (SM). Two independent assembly lines have been built up on which two flip-symmetric SM were assembled at the same time. On a third assembly line, two SM are connected with each other and superconducting bus-bars, helium-pipes and the instrumentation cabling and sensors are supplemented. After completion, the module is transported into the experiment-hall by means of a low-bed trailer and inserted into a cryostat module with precise alignment of its spatial position. As a last step, the modules are sequentially connected with each other.

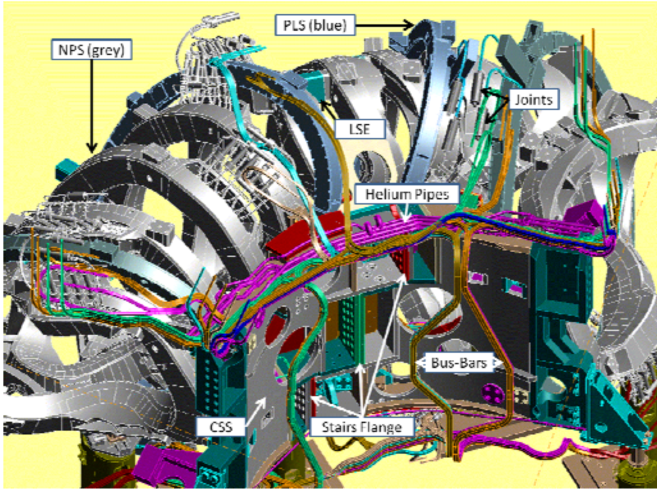

Fig. 1. Schematic diagram of the magnet module (10 NPS, 4 PLS) without PV

III. ASSEMBLY TECHNOLOGIES

A. *Semi modules (SM)*

It is the first work-package to thread the coils over the plasma vessel. Only in their final position there is sufficient clearance of few centimeters between coils and vessel for both a robust handling and placement of the thermal insulation onto the vessel. A coil must be tilted, shifted and rotated on the path to its final position (Fig. 2) without clashing the PV. The innermost coil of a SM has such a complex form that it matches neither from the left nor from the right over the vessel. Therefore SMs of the plasma vessel are divided into two sectors. These sectors are positioned and welded after the first coil is in place and before the subsequent coils are threaded. Planar coils are situated in tilted position over the five non-planar coils. For the assembly of planar coils, one has

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to lift simultaneously the already positioned non-planar coils. A single coil must be kept precisely into position but must be adjustable in all 6 degrees of freedom without influencing the position of other coils. Special tilting bearings (narrow support elements) must be installed (tolerance 0.1 mm) together with a coil [4]. For this, every coil is tentatively positioned, the distance to the neighboring coil is measured and the support element gets accordingly customized.

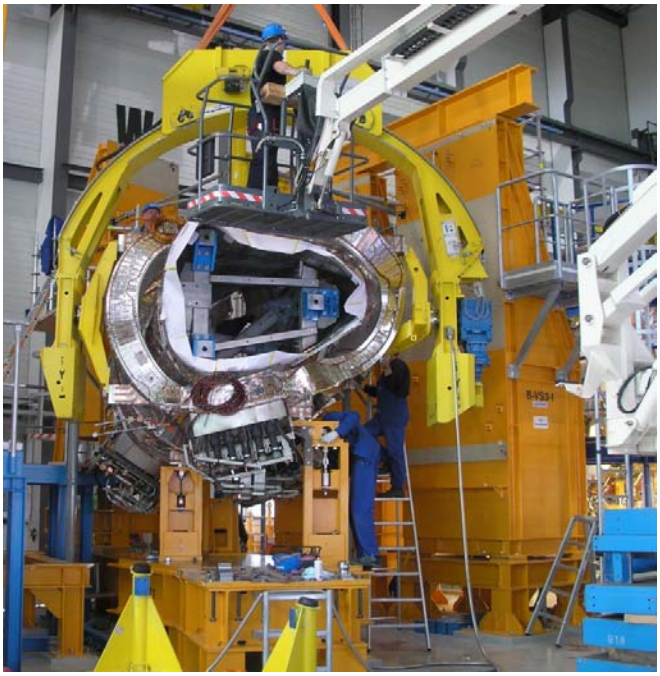

Fig. 2. Assembly Rig: Threading of non-planar coils over the plasma vessel

About six fiducial marks at every coil are used to align it by means of laser tracker measurements in a co-ordinate system that is represented by reference points in both the assembly rig and in the hall-building. Alignment results are shown in table 1. Every coil can be adjusted several times independently from other coils or vessel parts. The design requirements for the above rig and superstructures are 0.5 mm for their accuracy and stability. The assembly rig does not only hold the coils but also the vessel sectors with their full dead weight one-sided. The contour of the plasma vessel is deformable (many openings, 17 mm wall thickness). Indeed, the sectors deformed in the range of about 1 mm when they are lined up, although the sectors were temporarily stiffened. The above effects led inevitably to middle contour deviations of the vessel parts of up to 3 mm with local excess of up to 5 mm.

For the handling of the coils with 5 t of weight two special manipulators (threading units) were developed [3]. These are hanging in the crane and enable movements in 6 degrees of freedom. Threading paths were mathematically optimized for every coil-type to minimize the risk of clashes. The original plan was to use the derived threading-coordinates for the computer-aided control of the manipulator movements. It turned out to be much more economic, faster and more reliable to control the devices by well trained operators using well prepared documents. When the works ran routinely, it took just a few hours to bring a coil in its position. However, the entire assembly-run for one coil lasts some weeks including the extra positioning and the machining of support elements (Table 2). The above mentioned tools (rigs, supports, manipulators…) were designed and built by several companies. It lasted more than three years from the first conceptual ideas until the delivery of the last tool and about 2 Mio€ had to be spent. Over several months training sessions with mock-ups of coils and vessel sectors were made, ensuring a smooth start of the assembly operation.

The central support structure (ring segment) is put in front of the coil-set when all seven coils are in place and the vessel sectors are aligned, welded and thermally insulated. Each coil has got two extensions which are bolted to the ring segment [4]. The contact area at the extensions is designed as 5-sided form lock, i.e., at each side a customized 200 mm long wedge has to be welded to the extension to fill the as-built gap between coil-extension and the ring. A moulding procedure is used to take the as-built dimension of the gaps. Before the bolts are tightened it is checked that the remaining gap at the form-lock does not exceed the limit of about 0.3 mm. The plasma vessel is suspended in the magnet structure with three temporary pendulum rods and the accomplished SM (50 tons weight) is moved to the next assembly line.

B. *Modules*

Two flip-symmetric SMs are connected together. The stairs-shaped contact-flanges at both ring segments (Fig. 1) were manufactured with accuracy better than 0.1 mm. Both segments were already put together at the manufacturer site and finished in this clamping. Hence, the geometrical accuracy of the module is already pre-defined and no further alignment is necessary. Conical dowels in the flanges do help to regain the exact manufacturer position. The flanges are bolted together with Inconel screws and super-bolt nuts and complemented with 46 mm fixing pins. The reaming of the 46 mm fitting holes on site without lubricant was made by an industry service. The vessel parts are aligned to each other, welded from the inside and their thermal insulation with the cryo-shield is complemented in the connection area. Dye penetrant tests and leak tests are used to ensure the welding quality. Accumulated contour deviations of completed vessel modules of up to 8 mm locally have been measured. Lateral supports (LSE), (Fig. 1), are welded between each two adjacent coils [5] in parallel to the vessel works. Here it was a challenge not to lose the already achieved accurate coil position despite the massive weld seams of up to 25 mm thickness. For that purpose the coils position was monitored with laser pointers and laser trackers while the welding (MAG) was made in combination with local quenching by means of CO_2 icing. The loss of coil position precision turned out to be less than 0.3 mm. As a last mechanical work-package, two so-called cryo-feet are being assembled [6]. These are carrying the dead weight of the magnet module on slide bearings, enabling the thermal contraction during the cooling down to 4 K.

The most effortful work package at the completion of single modules is allotted to the installation of the bus-bar systems and the helium piping. Bus-bars are made from the same super conductor that was used for the coil fabrication. 24 bus-bars belong to one module. Two flip-symmetrically arranged coils of the same type are connected with each other; seven pairs altogether. The bus-bars are designed to be bifilar and connections for the neighboring modules and for the current leads are included. FZ Jülich delivered the bus-bars pre-bent (according to 3D CAD models), insulated and tested [8]. However, the ends need to be customized on-site, according to the as-built dimensions. The damage-free handling of up to 14 m long bus-bars is ensured through helium-filled balloons (“flying” bus-bars). The positioning of bus-bars is made with a local accuracy of +/-2 mm. Narrow areas are inspected with laser-scans. Essential for the entire accuracy is the positioning of the bus-bar supports. These supports are designed such that they provide a sensible direction-dependent equilibrium between strength (bus-bars need to be supported against the Lorenz forces) and flexibility (the MS deforms elastically under full load). About 80 different support-types which can be aligned in all 6 degrees of freedom have been installed with intensive metrology assistance.

Fig. 3. The Joint Assembly - Connection of Strands

A special challenge is the connection between bus-bars and coil terminals - the so-called joint [7]. It must be dismountable to ensure (in principle) the replacement of coils. It has to withstand peak pressures of 170 bars in case that coils are quenching and its transition resistance must be less than 5 nΩ at 2 T. There is a material transition since the bus-bar conduit is made from aluminum whereas the joint housing is made from steel. All parts in the interior of the joints must not be loose to avoid friction losses in the strands during changing magnetic fields. The development of the joints lasted about three years. The quality of the joint-works can hardly be completely checked on-site (for that the MS would have to be cooled to 4 K). Therefore every assembly step is exactly predefined and a written receipt must be signed after execution. An independent quality inspection checks visually the compliance of the instructions. Leak tests at weld seams and integrity tests of the electrical insulation are made on-site. In addition several joint samples are made on-site during the assembly work and tested in the Efremov Institute (St. Petersburg, Russia) at 4 K. They all confirmed the work quality with transition resistances of less than 5 nΩ.

Customized welding procedures were developed for lip welds at the joint housing and for aluminum welds at the aluminum/steel transition pieces. These developments lasted for about two years. The work at the joints (Fig. 3) proceeded routinely only as of the third module. Most of the bus-bar assembly work was made by a team of the IFJ (Cracow, Poland), which worked on CERN before. Voltage taps are welded to the conductor ends for the later quench detection. The joints are insulated with a manual wet-wrapping procedure and with an additional Kapton® foil underneath. This work requires special care because of the bad accessibility and the bad stability of the wrapping before it cures. Paschen tests with up to 5 kV with local test chambers ensure the necessary quality. A conductive paint on the insulation accomplishes the bus-bar work. For the helium pipe work, about 200 pre-bent pipe sections, bellows and flexible hoses are installed on supports and welded with each other. All weld seams are leak tested and x-rayed. In conjunction with the above work, many sensors and the associated instrumentation cabling are installed and tested. The assembly of the bus-bar, the pipe work and the instrumentation in a two-shift work system lasted 60 weeks for the first module and 37 weeks for the last module.

C. *The connection of the modules to the torus*

The cryostat module is completed when a module is put into the experiment hall (Fig. 4). The connection of modules starts immediately after the second module is in place with putting six customized shims in the gap between the flanges of the two neighboring ring segments. Every shim weights 17 kg and is machined with an accuracy of 0.1 mm. The flanges are bolted in the similar manner as the semi-module flanges. Additional supports are stiffening the neighboring coils at this location. Of those, the two lateral supports, need a precise form-lock with the coil body ensuring a remaining gap of less than 50 μm before the connection is tightened [9]. For that, the wedge-shaped contact contour at every coil is laser scanned and their position is laser tracker measured. With these data high-precision parts are machined and installed. Further works comprise the connection of adjacent bus-bars, pipe works and cablings which are made in a similar manner as described above. With every module the torus of the magnet system is closed stepwise.

The last activity is the assembly of the current leads (CL). The assembly technology is presently being developed in cooperation with the PPPL/ORNL (USA) to cope with the very limited installation space and with the weight and the complexity of the components affected [10]. The first CL pair shall be installed in 2012.

IV. ACCURACY

Table 1 summarizes the figures achieved without the inaccuracy for both the measurement (0.3 mm) and the coil manufacturing (about 2 mm). Laser tracker measurements and the photogrammetry are used to determine the as-built position of coils and coil groups. Five measuring systems are simultaneously in use for the daily business. The total geometrical error of the torus (70 coils) is being minimized since every module is positioned finally under at least partial consideration of the geometrical deviation of the other single modules [12]. The statistical evaluation of the deviations of the different assembly stages in combination with the manufacturing deviations is expected to result in a relative magnetic field perturbation below 2*1E-4 [11]. The total geometrical error of the torus (70 coils) is expected to lie below 1E-4. In addition, external normal conductive coils will improve the overall accuracy of the magnetic field [1].

V. ASSEMBLY TIMES, PLANNING AND DOCUMENTATION

Table 2 summarizes the assembly duration of designated work packages. The difference between the first module and the fifth module shows the acceleration potential due to learning effects and the optimizations of both the processes and the equipment. The estimate shows the early assumptions at the time of the assembly-beginning in 2005. About 50% of the workforce for the assembly was hired from the industry. This applies to workers, technicians and engineers. 300000 man hours were approximately needed one-site for the assembly of the five single magnet modules. About 10% out of this sum each was needed for metrology services, for Paschen and leak tests and for special welding works. The figures contain also the expenditure for associated development works and the effort for the component preparation which is not described here. The experiment hall has an area of about 900 m². In addition 1500 m² are needed for the assembly of the magnet system only.

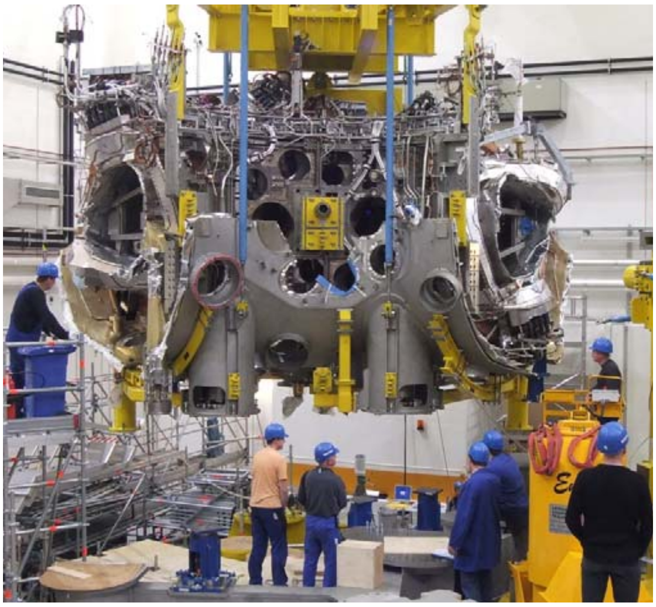

Fig. 4. An accomplished magnet module in the lower cryostat shell on the way to its final position

Quality assurance and assembly plans (travelers) prescribe the single work steps which have to be done. Additional work and inspection instructions describe the work more in detail, including part lists, drawings etc. Up to five engineers were needed permanently to draft, release and optimize these documents (140 files per module) in direct contact with the ongoing work for the MS. The assembly of the entire W7-X facility is running as planned. Only marginal plan deviations occurred in the last five years.

TABLE 1 ASSEMBLY ACCURACY OF THE MAGNET SYSTEM

Stage	**Maximum deviations from nominal positions at the fiducials**
Single coil	+/- 1.5 mm
Semi-module (7 coils)	+/- 2.5 mm
Module (14 coils)	+/- 3.5 mm
Torus (70 coils; estimate)	+/- 6,5 mm

TABLE 2 ASSEMBLY TIMES IN WEEKS

Stage	**Estimate**	**1st module**	**5th module**
Coil process	5	8,5	1,5
Semi-module	42	76	30
Module	56	85	63
Current Leads (one pair)	14	=	=

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